HYDRO-ELECTRIC POWER STATIONS

BY
arker
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SECOND EDITION

THOROUGHLY REVISED AND RESET

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PREFACE TO SECOND EDITION

In the Preface to the First Edition of this book it was predicted that the rapid growth of power demands and the rising cost of fuel would lead, in the very near future, to greatly increased activity in the development of our water-power resources. This prophecy has been so fully justified that the standards of that day are in many instances obsolete, and it has been necessary to rewrite practically all of the more important sections of the book.

The rapid advances made within the past few years in hydro-electric engineering have affected both the hydraulic and the electrical elements. It should also be remembered that the increased size of the typical modern power development calls for the adoption of an entirely new point of view in the consideration of the economic problems involved.

One of the most important changes in the hydraulic equipment of the hydro-electric plant has been the introduction of the spreading and hydraucone types of draft tubes and the propeller type of turbine runner.

On the electrical side, the construction of larger and larger units has led to radical changes in design. The concentration of immense amounts of power has created a demand for more rugged switching apparatus, capable of rupturing enormous short-circuit currents. At the same time, modern industrial conditions have made it necessary to adopt higher standards of safety and continuity of service, with the result that very reliable relay schemes have been devised. Many improvements in this class of apparatus have been made within the past few years.

The present volume sets forth the most recent practice along all the lines mentioned above and in all other matters essential to the design and operation of hydro-electric power stations. In view of the thoroughness with which the different subjects have been treated, it is believed that this edition will be of considerable service, both as a text-book for students of engineering and as an aid to operators, engineers and managers of hydro-electric power stations.

The authors wish to take this opportunity to express their appre-

ciation and thanks to those who have so kindly and willingly assisted in this revision with their suggestions and advice. Among these may especially be mentioned Mr. Lewis F. Moody, of the I. P. Morris Company, who has supplied much valuable material for the section on Turbines, and Mr. O. C. Traver, of the General Electric Company, who has similarly contributed considerable material and advice in connection with the section on Relays. The section on Transformer Connections has been taken from a treatise on the subject written by Messrs. E. A. Lof, L. F. Blume, and A. Boyajian, all of the General Electric Company, and the section on Transformer Drying has been contributed by Mr. F. I. Manvel, of the same company.

David B. Rushmore.
Eric A. Lof.

Schenectady,
September, 1923.

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HYDRO-ELECTRIC POWER STATIONS

CHAPTER I

GENERAL INTRODUCTION

HISTORY OF WATER POWER AND ELECTRICAL DEVELOPMENTS

THE use of water power for industrial purposes dates back to very ancient times. Crude current wheels were familiar to the Chinese on the Yellow River and the Hamites on the Nile and Euphrates fully three thousand years ago. These wheels operated entirely by the kinetic energy of the moving water, and the power thus obtained was utilized for raising the water of the rivers for irrigating the arid land and also for grinding corn and other simple applications. Similar current wheels, although necessarily of improved design, have been most widely utilized and, while very inefficient, are still used for minor works designed for irrigation and other purposes in many countries.

The first radical change in the art was the use of channels, by which the water could be conducted and directly applied to undershot wheels. This improvement resulted in the utilization of some 30 per cent of the theoretical water power, and the system maintained its prominence until almost the middle of the eighteenth century, when the overshot wheel was invented by John Smeaton, who showed that if the bucket wheel was changed into an overshot form, its useful efficiency would be increased to over 60 per cent. In this type of wheel the energy of the water was applied directly through its weight by the action of gravity and yielded a very high efficiency. Overshot wheels were formerly built of great size. One at Laxey, Isle of Man, constructed about 1865 and said to be still in operation, is 72 feet 6 inches in diameter and develops 150 horse-power. A number of overshot wheels are also in use at old mills in the Catskill Mountains in New York State.

The breast wheel, which followed the overshot wheel, was developed in England during the latter part of the eighteenth century and was

used for a great number of years. It consisted of a circular drum, having on its periphery a series of buckets, the sheathing of the drum forming their bottom. They were operated partly by gravity and partly by kinetic energy, and the water was applied through a flume and controlled by gates. Below these was located the "breast" which consisted of a concave cylindrical surface of planking, concentric with the wheel. The clearance was very small, thus preventing the water from spilling out of the buckets until it had reached the lower level. This type of wheel gave an efficiency of about 70 per cent.

The wheel types described above, however, have now been almost entirely superseded by the turbine, and are therefore so nearly obsolete that they may be considered as of historical interest only. While the fundamental principles of the turbine may be distinguished in wheels used in the sixteenth century, the principal developments were made during the last century. In the turbine the water acts mainly by impulse or reaction or both, and the velocity has a definite relation to the head.

In 1823, M. Fourneyron began his experiments on the radial outward-flow turbine, the first example of which was installed at Pont Sur l'Ognon in France, in 1827. Its principle consisted in an outward discharge from a pipe, to a wheel with curved buckets placed outside of the apertures of discharge. The buckets, revolving from the action of the water, finally discharged it at the circumference with its force exhausted. The tube which supplied the water was closed at the bottom by a concave cone surrounding the wheel shaft, which passed up through it in a pipe, so as not to be exposed to the water. This cone was surrounded by a number of guide plates, which directed the water to the buckets in the proper tangential direction.

The axial discharge turbine was first built by Henschel & Son in Germany in 1837. There has always been doubt as to whether this turbine should be attributed to Jonval or to Henschel. Jonval thoroughly described the basic idea in a patent dated 1841, and it is quite possible that he was working on the proposition as early as Henschel. It proved to be far superior to the outward-discharge type and almost entirely eliminated the latter.

The inward-flow wheel, in which the action of the Fourneyron turbine is reversed, was patented by S. B. Howd, of Geneva, N. Y., in 1836, and seems to have been the origin of the American type of turbine. Very great improvements were made, however, in the construction by James B. Francis about 1847, and many regard him as the originator. The Francis turbine of to-day has displaced all other types of reaction turbines, and, with its rapid development, radical departures have been

made from the strictly radial inward-flow, with the result that the Francis turbine of to-day is of a combined radial or diagonal inward-discharge type. A transition period in the design of turbines occurred between 1890 and 1900, when the turbine was being modified to meet the requirements of electric generator drive, one phase of this transition being an increased complexity marked particularly by the adoption of multi-runner units.

Another change took place in 1911 and 1912, marked by the return to greater simplicity and the readoption of the single-runner vertical turbine. This period also marks the introduction of the metal speed ring built into the concrete substructure, in combination with a concrete volute casing. Since that time this construction has been universally adopted as standard practice for vertical units under low and moderate heads.

After having remained practically stationary in its development for a number of years, the design of reaction turbines has shown a surprising number of changes and improvements within the last three years. The introduction of the propeller type of runner, and of the hydraucone and spreading types of draft tubes, etc., has thus made possible the extension of the range of available speeds, so that extremely high specific speeds are now obtainable with satisfactory efficiency. Although great progress has been made in the attaining of higher speeds, another problem remains to be investigated; this is the extension of the application of these high-speed turbines to higher heads.

The impulse wheels were among the earliest forms used. Thus, the *rouet volant*, or flutter wheel, was used for centuries in India, Egypt, Syria and Southern France. It consisted of flat, vertical vanes projecting radially from a vertical wooden shaft, the water jet from the feeding spout striking the vanes tangentially near their ends. It was not, however, until 1853 that this type of wheel was given a scientific consideration in this country. A study of it was then made by Jearum Atkins, while its practical development must be credited to Lester A. Pelton, who, in 1882, and following years, made radical improvements in its design. This type of wheel is now extensively used in the West, where the high heads make such a wheel necessary. The fundamental principles remain practically the same as in earlier types, recent developments consisting chiefly of the adoption of larger and larger units, with refinements in design. Considering the enormous forces to which these wheels may be subjected, very careful consideration must naturally be given to the proper design of the buckets and their fastening to the wheel disc.

The first great water power developments were made in the New England States. The textile industry was destined to expand rapidly and the water power of the streams was its supporting ally. Under this influence, the first great water power was developed on the Merrimac River, in 1822, where subsequently the City of Lowell became a great cotton manufacturing center. Near Lowell there were soon developed the equally prominent water powers on the Merrimac River at Manchester, in New Hampshire, and Lawrence, in Massachusetts. Each of these developments had a capacity of 10,000 to 12,000 horse-power, and each was chiefly devoted to the manufacture of cotton goods, as were the water powers of Cohoes (1828) in New York, and Lewiston (1849), in Maine. The Connecticut River water power at Holyoke (1848) was largely devoted to the manufacture of paper, as were the Fox River powers in Wisconsin, at a later date. The water powers on the Genesee River at Rochester, N. Y. (1856), and on the Mississippi River at Minneapolis (1857), were largely devoted to the manufacture of flour.

In 1861, the development of the mighty power of Niagara Falls was begun, a canal being built through the town to a power-house at the edge of the gorge, below the falls. The Niagara Falls Hydraulic Power & Manufacturing Company was formed in 1872, and during the first years its operation consisted in furnishing water to numerous water wheels of different manufacturing enterprises. The inefficiency of this method, however, soon became apparent, and a central power-house was built in 1881, the energy being transmitted to the factories along the edge of the cliff, by means of ropes, belts and shafts.

Different opinions exist as to the time at which the first transmission of electricity took place. Its possibility was pointed out as early as 1850 and possibly earlier, and it is claimed that in 1858 electricity was utilized, for the first time, for driving a commercial machine. This was in the artillery works of St. Thomas d'Aquin, France, where a dividing machine was driven by an electric motor, which derived its current from an adjacent battery. Though the electric motor existed long before the dynamo, it attained no prominence until after the practical demonstration of the latter. As long as the galvanic battery constituted the source of power, the application was naturally restricted. Another limitation was found in the defective construction of the earlier motors; their counter E.M.F. was comparatively weak, and hence the work which could be obtained from them was small in comparison with the power expended and their size.

While the principle of the reversibility of the electric motor seems to have been known as early as 1850, it was the practical experiments

carried out by Gramme, at the Vienna Exposition in 1873, that clearly demonstrated the practical importance of this property. Gramme is, therefore, generally given the credit for having first practically demonstrated the possibility of employing the electric current for transmitting energy from one place to another. His experiments at this Exposition consisted in transmitting current from a machine working as a generator to a second machine, about 550 yards distant, working as a motor driving a pump.

In 1878, a motor was installed at the sugar works at Sermaize, France. It was used to operate a hoist and derived its current from a steam-driven Gramme generator. The application of water power for driving dynamos followed shortly, and the same year a water-wheel-driven generator was installed at the Shaw Chemical Works, England, and power supplied to a motor 150 yards distant, for driving miscellaneous tools. In 1882, the first commercial central stations for lighting began operation in London and New York, and the same year marked the building of the first hydro-electric central station in the United States, at Appleton, Wisconsin (Figs. 1 and 2).

In the above systems, and in several others, the electric current was transmitted for very short distances only; but in 1882 Marcel Deprez built the first long-distance transmission line from Miesbach to Munich, a distance of 37 miles. It was built purely for experimental and demonstration purposes, 2400-volt direct-current being used. The results proved to be very encouraging and financial support was obtained for a larger project. Thus, in 1884, Deprez began preparations for the Criel-Paris transmission, which was completed in 1886. In this, 20 amperes direct current was transmitted the 25-mile distance, at a potential of 7500 volts, the transmission efficiency obtained being about 32 per cent.

The first A.C. transmission system was the one at Cerchi, Italy, installed in 1886 and known as the " Cerchi Tivoli-Rome Plant." The equipment of this station consisted of two 150 H.P. steam-driven, single-phase Ganz generators designed to operate at 112 volts. Transformers having a ratio of 1 : 18 were used to step from this voltage up to 2000, at which voltage energy was transmitted to Rome, a distance of 17 miles. In 1889 the capacity of this steam plant was increased to 2700 H.P.

In 1887, Tesla, Ferraris and Bradley pointed out the advantages of the three-phase over the single-phase system, but it was not until 1891 that the first commercial three-phase transmission line was put into operation. This was the 112-mile Lauffen-Frankfort line, supplying a lighting load to the City of Frankfort. The power-house installation

Fig. 1.—Exterior View of First Hydro-Electric Central Station in United States at Appleton, Wisconsin. Installed in 1882. Capacity 250 lights.

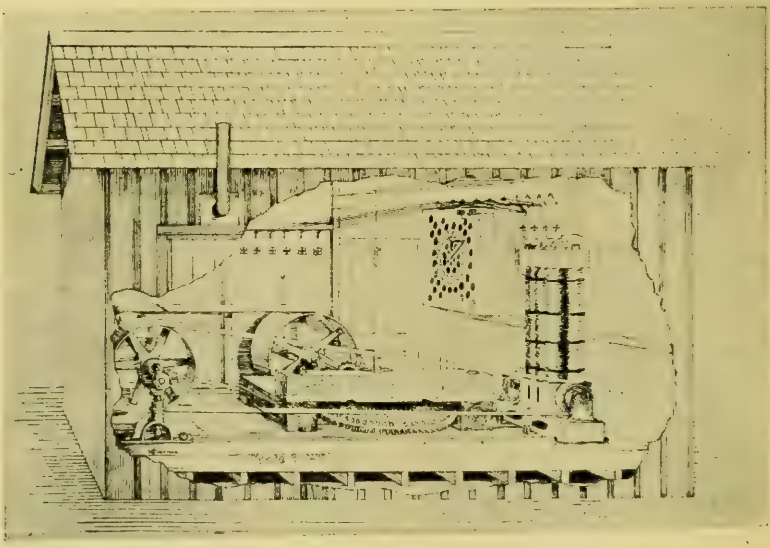


Fig. 2.—Interior View of First Hydro-Electric Central Station in United States at Appleton, Wisconsin.

consisted of one 225-kw. three-phase generator, direct-connected to a water wheel operating under a head of 10 feet. The line voltage was 12,000.

In the United States, the first A.C. hydro-electric installation was the one at Oregon City, built by the Willamette Falls Electric Company, and now owned by the Portland Railway, Light and Power Company. This installation took place in 1889 and the plant consisted of two 300-H.P. Victor wheels belted to 4000-volt single-phase generators, the power being transmitted to Portland, 13 miles distant. In 1890,

FIG. 3.—Power House, Mississippi River Power Company, Keokuk, Iowa.

shortly after the Willamette Falls Electric Company had completed their installation, the Telluride Power Company installed at Ames, Colorado, two 150-kw. single-phase generators directly connected to Pelton water wheels operating under a head of 500 feet. Power was transmitted to Telluride, a distance of 5 miles, at 3000 volts.

In 1892, another single-phase transmission plant was installed in California and delivered power to Pomona, approximately 13 miles distant, and about 29 miles to San Bernardino. The voltage at the beginning of operation was 5000, which was higher than any voltage used commercially before that time; but on February 16, 1893, this was raised to 10,000 volts; and on May 2, 1893, by connecting their

transmission lines all in series, 120 kw. was carried 42 miles with a transmission efficiency of 60 per cent, at that time a great achievement and an indication of the possibilities of electric transmission of power.

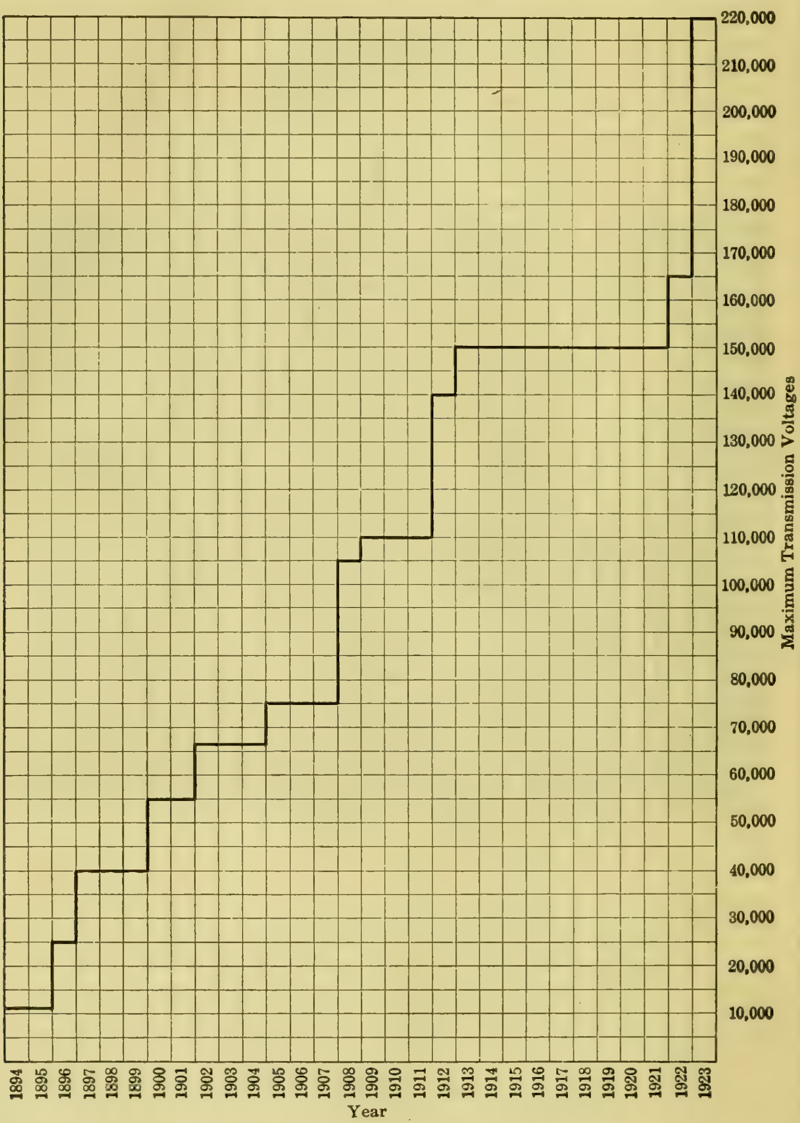


FIG. 4.—Commercial Transmission Voltages.

To Southern California also belongs the distinction of having the first commercial polyphase transmission system installed and operated

in the United States. In 1893 a generating station was built by the Redlands Electric Light & Power Company (now the Southern California Edison Company), at the mouth of Mill Creek Canyon. The plant consisted originally of two 250-kw., 2400-volt, three-phase, Y-connected generators, running at 600 R.P.M., and driven by Pelton water wheels under a head of 295 feet. The power was transmitted for a distance of $7\frac{1}{2}$ miles to Redlands and there used for lighting and industrial motor applications.

Before the end of the same year, another polyphase plant was installed at Hartford, Connecticut, where 400 kw. was transmitted 11 miles at 5000 volts. This plant replaced a single-phase installation which had been delivering power for lighting over the same line since 1891. With these plants, began the era of hydro-electric power transmission in the country, and statistics show that nearly three hundred plants were in actual operation about 1896. Rapid progress has been made in recent years in the size and efficiency of hydro-electric apparatus. The 55,000 horse-power turbines, with their 45,000 kv.a. generators, were not yet in operation at the Queenston plant at Niagara Falls, before it was decided to install units of 70,000 horse-power and 65,000 kv.a., respectively, in the Hydraulic Power Company's station, also at Niagara Falls. Single plants with capacities of half a million horse-power of installed machinery will soon be an accomplished fact at the above-mentioned Queenston development.

Similarly, a radical increase has also been made recently in transmission voltages, as seen from Fig. 4. For a number of years, 150,000 has represented the highest transmission voltage in commercial use. In 1922, the Caribou System of the Great Western Power Company began operating with 165,000 volts, and 1923 will witness the first use of 220,000 volts by the Southern California Edison Company. The Pacific Gas and Electric Company is also installing equipment for this voltage, the operation to be commenced at 165,000 volts by auto-transformer connection and increased to 220,000 volts when the load demands.

The limit of transmission voltage is not yet in sight, and the quarter-million voltage mark may be the next prospective limit. It is probable that such extremely high voltages will pay only where there are large amounts of power available for transmission, and where the demand extends over the greater part of the day. Under any other conditions, the cost per kilowatt-hour would be prohibitive.

HISTORICAL REVIEW OF WATER-WHEEL DEVELOPMENT

1740 Barker's Mill, the simplest type of tangential outflow turbines, was invented. It had radial arms and operated purely by reaction.
1823 M. Fourneyron began his experiments with the radial outward-flow turbine.
1826 A radial inward-flow turbine was proposed by Poncelet.
1827 The first Fourneyron turbine was erected at Pont Sur l'Ognon, France.
1836 Samuel B. Howd of Geneva, N. Y., obtained a patent on an inward-flow turbine.
1837 Fourneyron erected a turbine at St. Blaise, Switzerland, which operated under a head of 354 feet.
1837 O. Henschel, of Cassel, Germany, invented the downward axial-discharge turbine, later known by the name of Jonval or Koechlin.
1841 The first axial-discharge wheel was introduced into practice by the French engineer, Jonval.
1842 James Whitelaw, of Paisley, developed an improved type of Barker's Mill, which was erected on Chard Canal. This wheel had spiral tapering arms so curved that the water flowed radially when the wheel was running at proper speed.
1844 A Fourneyron turbine, constructed by Uriah A. Boyden, was erected at Appleton Company's cotton mills in Lowell, Mass.
1847 James B. Francis made radical improvements in the inward-flow turbine.
1850 About this time the Jonval turbine was introduced in America by Elwood and Emile Geyelin, of Philadelphia.
1853 Jearum Atkins considered the impulse wheel scientifically, being the first to do so in this country.
1859 The "American" or mixed-flow turbine was designed.
1882 Lester A. Pelton made radical improvements in this type of wheel.
1895 The Niagara Falls Power Company built first plant at Niagara Falls, N. Y.
1911 Vertical single-runner type of Francis reaction turbine, with concrete volute casing, was first used by Appalachian Power Co., New River, Va.
1913 Mississippi River Power Company began operating 10,000 H.P., 57.7 R.P.M. turbines under a head of 32 feet.
1914 Cedar Rapids Mfg. and Power Company, on the St. Lawrence River, commenced operating 10,800 H.P., 55.6 R.P.M. turbines under a head of 30 feet.
1920 The hydraucone and spreading types of draft tube were introduced.
1920 Hydraulic Power Co., Niagara Falls, N. Y., installed 37,500 H.P. Francis reaction turbines, operating at 150 R.P.M. and 215 feet head.
1920 High-speed propeller-type runner, for low and moderate heads, was introduced.
1921 Fifty-five thousand H.P. Francis reaction turbines, operating at $187\frac{1}{2}$ R.P.M. and 305 feet head, were installed at Queenston plant of Hydro-Electric Power Co., Niagara Falls, Ont.
1921 Twenty-five thousand H.P. vertical Francis reaction turbine, operating at 600 R.P.M. and 800 feet head, was installed by Southern California Edison Co., Kern River No. 3 plant.
1921 Thirty thousand H.P. impulse wheels, operating at 171 R.P.M. and 1008 feet head, were installed at Caribou station of Great Western Power Company, Cal.

1922 Forty thousand H.P. Francis reaction turbines operating at 257 R.P.M., 421 feet head, were installed by Pacific Gas and Electric Co., Pitt River No. 1 plant.

1923 Shawinigan Power Company installed 41,500 H.P. turbine, operating at 138.3 R.P.M. under 145 feet head.

1923 First large installation of diagonal propeller-type turbines, 28,000 H.P. units operating at 138.5 R.P.M. under 56 feet head, was completed by Manitoba Power Company at Great Falls, Manitoba.

1923 Thirty-five thousand H.P., 514 R.P.M. Francis reaction turbines, operating under a head of 857 feet, were installed by the Portland Railway and Light Co., in their Oak Grove Development.

1923 Seventy thousand H.P. Francis reaction turbines, operating at 107 R.P.M. and 213 feet head, were installed by Hydraulic Power Co., Niagara Falls, N. Y.

HISTORICAL REVIEW OF THE PROGRESS OF ELECTRIC POWER TRANSMISSION

1820 A. M. Ampere announced his discovery of the dynamical action between conductors conveying electric currents; currents flowing in the same directions attracting and in opposite directions repelling.

1821 Michael Faraday discovered the electromagnetic rotation, causing a wire conveying a voltaic current to rotate continuously around the pole of a permanent magnet.

1831 Faraday discovered the principles of electromagnetic induction and laid the foundation for all subsequent inventions which finally led to the production of electromagnetic or dynamo-electric machines.

1832 H. Pixii built a magneto-electric machine consisting of a fixed horseshoe armature, wound over with insulated copper wire, in front of which a horseshoe magnet revolved about a vertical axis.

1832 H. Pixii invented the split-tube commutator for converting the alternating current into continuous current.

1840 Henry Pinkus proposed and patented the principle of transmitting electric energy through wires to an electric motor on a railway car.

1841 Prof François Nollet, Brussels, proposed the electrical utilization of water and wind power for driving dynamos.

1850 Jacobi claimed that an electromagnetic machine could also be worked as a magneto-electric machine and vice versa.

1851 Dr. Sinsteden suggested the use of currents produced by magneto-electric machines for driving electric motors.

1855 Bessolo, Italy, suggested and patented a scheme for the electrical utilization of natural forces, and long-distance transmission of electrical energy for power purposes.

1857 E. W. Siemens invented the drum-wound armature and made an improvement in the shape of field magnets.

1858 Beams of intense electric light were obtained from the voltaic arc, by Faraday.

1858 Eugene Regnault worked a Froment electrical motor by the current from a Clarke magneto-electric machine driven by a mechanical motor.

1858 A dividing machine was driven by an electric motor at the Artillery Works of St. Thomas d'Aquin, France. Current was obtained from a battery.

1864 Cazel obtained a French patent on an electric railway system, in which one or more magneto-electric machines were to be driven by hydraulic or wind motors, and the current generated conveyed to a rotary car motor by wires and the track rails.

1866 Dynamos utilizing Siemens' principle began to be built commercially and were employed for producing electric light.

1866 Felice Marco, Italy, was granted an Italian patent for the electrical utilization of water power.

1867 Prof. Pfaundler, of Innsbruck, experimented with a Kravogl electric motor exhibited at the Paris Exposition, and found that it could also be used for generating electric currents.

1870 The Gramme ring dynamo was invented.

1870 Jacobi worked an electric motor by means of a secondary battery.

1873 Gramme and Fountaine discovered that the action of the dynamo is reversible and made the first public demonstration of power transmission at the Vienna Exposition. Current was transmitted from a machine working as a generator to a second machine 550 yards distant, working as a motor and driving a pump.

1875 Alcide Girin was granted a French patent for the combination of electromagnetic inductive apparatus and a certain number of induction coils in order to obtain in the secondary circuits a lower tension and a higher intensity than in the primary circuits.

1876 Jablochkoff's arc lamp was invented.

1876 Wallace-Farmer dynamo was exhibited at the Philadelphia Centennial Exposition.

1878 A motor was installed in the sugar works at Sermaize, France, for operating a hoist. Current was obtained from a steam-driven Gramme generator.

1879 First commercial arc lamp system (Brush) was installed in Cleveland.

1879 Edison incandescent lamp was invented, and first complete system of incandescent lighting installed at Menlo Park.

1879 Siemens and Halske installed the first electric railway in which current was generated by dynamos. At the Berlin Exposition a line of 550 yards was laid down, upon which a small locomotive drew passenger cars, merely as a novelty.

1881 Carpentier and Deprez were granted a patent for a system of transporting electricity to a distance and transforming it.

1882 Gaulard and Gibbs suggested the transformer for practical operation.

1882 Marcel Deprez built the first long-distance experimental line, from Miesbach to the Exposition in Munich, a distance of about 37 miles. He transmitted one-half horse-power direct current at a pressure of 2400 volts.

1882 First hydro-electric central station, with a capacity of 250 lights, was installed at Appleton, Wis.

1882 First commercial central station for incandescent lighting began operation in London.

1882 Pearl Street Station of Edison Electric Illuminating Company began operation in New York.

1883 "Feeder and Main" system was first used.

1883 "Three-wire" system was first used.

1884 Dr. J. Hopkinson clearly established the fact that similar alternators could be run as generators and motors. This was first practically demonstrated in 1889, by Mordey.

1884 American Institute of Electrical Engineers was organized.
1885 First transformer was built in this country, by Wm. Stanley at Great Barrington, Mass.
1885–88 Nicola Tesla and Galileo Ferraris independently invented the polyphase induction motor and pointed out the advantages of the three-phase system.
1885 National Electric Light Association was organized in Chicago.
1886 First regular 133-cycle, single-phase lighting plant was installed in Buffalo.
1886 Criel-Paris transmission was completed. Twenty amperes direct-current was transmitted for a distance of 25 miles at a potential of 7500 volts.
1886 Sprague installed the first electric street railway in this country, at Richmond, Va.
1886 The first A.C. transmission system was installed at Cerchi, Italy, 150 H.P. being transmitted for 17 miles at 2000 volts, single phase.
1887 Tesla, Ferraris and Bradley pointed out the advantages of the three-phase system.
1888 Rotating-field principle of alternating-current generators was invented.
1889 The first A.C. hydro-electric installation in the United States was completed by the Willamette Falls Electric Co., 300 H.P. being transmitted for 13 miles at 4000 volts, single-phase.
1891 Lauffen-Frankfort Transmission. 110 H.P. was transmitted from Lauffen to the Exposition at Frankfort, a distance of 112 miles at 12,000 volts, three phase.
1891 Sixty cycles introduced in United States.
1892 The first long-distance transmission in United States at San Antonio, Cal. 800 H.P. was transmitted 28 miles at 10,000 volts single phase.
1893 Twenty-five cycles introduced.
1893 The first three-phase hydro-electric plant in United States was installed at Redlands, Cal.
1895 The first 5000-H.P. generators were installed at the Niagara Falls Power Company.
1896 25,000-volt system of the Pioneer Electric Power Company, Utah.
1903 60,000-volt system of the Guanajuato Power and Electric Co., Mexico.
1908 110,000-volt system of Au Sable Electric Company, Grand Rapids, Mich.
1913 150,000-volt system of the Pacific Light and Power Co., Los Angeles, Cal.
1918 First completely automatic hydro-electric power station of the Iowa Ry. & Lt. Co., Cedar Rapids, Iowa, was installed.
1920 First 32,500 kv.a. generators were installed at the Hydraulic Power Company's plant, Niagara Falls, N. Y.
1921 First 45,000 kv.a. generators were installed at Queenston plant, Hydro-Electric Power Commission, Niagara Falls, Ont.
1921 First oil-circuit breakers having a rupturing capacity of $1\frac{1}{2}$ million kv.a. were installed.
1921 Isolated-phase bus-structure arrangement was first used.
1922 165,000-volt transmission, Caribou system of Great Western Power Co., California.
1923 First 65,000 kv.a. generators were installed at Hydraulic Power Company's plant, Niagara Falls, N. Y.
1923 220,000-volt transmission. Southern California Edison Company's Big Creek System.

WATER POWERS OF THE WORLD

An estimate of the developed and potential water power of the world, for the year 1920, in horse-power, has recently been completed by the United States Geological Survey, and is published in great detail in their World Atlas of Commercial Geology. The figures, which are given in part in Table I, represent 75 per cent of the theoretical power from flow available at least 75 per cent of the time.

TABLE I

ESTIMATE OF POTENTIAL AND DEVELOPED WATER POWER IN 1920, IN HORSE-POWER

	Developed.	Potential.
The World		
North America	12,210,000	62,000,000
South America	424,000	54,000,000
Europe	8,877,000	45,000,000
Asia	1,160,000	71,000,000
Africa	11,000	190,000,000
Oceania	147,000	17,000,000
Approximate total	23,000,000	439,000,000
North America		
Mexico	400,000	6,000,000
United States	9,243,000	28,000,000
Alaska	40,000	2,500,000
Newfoundland	60,000	400,000
Canada	2,418,000	20,000,000
Costa Rica	15,000	1,000,000
Guatemala	4,000	1,500,000
Honduras	3,000	1,000,000
Nicaragua	400	800,000
Salvador	2,700	200,000
Panama	13,300	500,000
West Indies	12,500	150,000
Approximate total	12,210,000	62,000,000
South America		
Argentina	25,000	5,000,000
Bolivia	12,000	2,500,000
Brazil	250,000	25,000,000
British Guiana	....	2,500,000
Dutch Guiana	....	800,000
French Guiana	....	500,000
Chile	60,000	2,500,000
Colombia	25,000	4,000,000
Ecuador	2,500	1,000,000
Paraguay	200	2,000,000
Peru	36,500	4,500,000
Uruguay	....	300,000
Venezuela	12,500	3,000,000
Approximate total	424,000	54,000,000

Europe

	Developed.	Potential.
Sweden	1,200,000	4,500,000
Norway	1,350,000	5,500,000
Finland	185,000	1,500,000
Russia	100,000	2,000,000
Esthonia, Latvia, Lithuania	20,000	200,000
Poland	80,000	200,000
Ukraine	40,000	425,000
Region of the Caucasus	5,000	5,000,000
Hungary	30,000	150,000
Czechoslovakia	50,000	420,000
Jugo-Slavia	125,000	2,600,000
Austria	205,000	3,000,000
Rumania	30,000	1,100,000
Bulgaria	8,000	1,200,000
Greece	6,000	250,000
Turkey	....	Small
Albania	1,000	500,000
Italy	1,150,000	3,800,000
Switzerland	1,070,000	1,400,000
Germany	1,000,000	1,350,000
France	1,400,000	4,700,000
British Isles	210,000	585,000
Belgium	700	Small
Denmark	1,500	2,000
Netherlands	....	....
Spain	600,000	4,000,000
Portugal	10,000	300,000
Iceland	....	500,000
Approximate total	8,877,000	45,000.000

Asia

Chinese Republic	1,650	20,000,000
India	150,000	27,000,000
Asia Minor	500	500,000
Arabia	....	....
Persia	....	200,000
Afghanistan	2,000	500,000
Siberia	....	8,000,000
French Indo-China	....	4,000,000
Siam and Malay States	4,500	4,000,000
Chosen (Korea)	2,620	500,000
Japan	1,000,000	6,000,000
Approximate total	1,160,000	71,000,000

Africa

Tangier	....	50,000
Morocco	....	250,000
Algeria	130	200,000
Tunis	....	30,000
Tripoli	....	Small
Eritrea	....	Small
British Somaliland	....	Small
Italian Somaliland	....	Small
Gold Coast and British Togoland	....	1,450,000
Liberia	....	4,000,000
Sierra Leone	....	1,700,000
Senegal	....	250,000
Rio de Oro	....	Small
Gambia	....	Small
Portuguese Guinea	....	Small
Union of South Africa	5,000	1,600,000
Angola	4,000	4,000,000
Southwest Africa Mandate	....	150,000
Belgian Congo and Belgian Mandate	250	90,000,000
French Congo	....	35,000,000
French Mandate in Kamerun	....	13,000,000
Nigeria and British Mandate in Kamerun	....	9,000,000
Rhodesia	....	2,500,000
Tanganyika	800	2,700,000
British Central Africa	....	1,200,000
British East Africa	900	4,700.000
Portuguese East Africa	....	3,700,000
Bechuanaland	....	20,000
Abyssinia	....	4,000,000
Egypt	....	600,000
Ivory Coast, Dahomey and French Togoland	....	2,850,000
French Guinea	....	2,000,000
French Soudan	....	1,000,000
Madagascar	100	5,000,000
Approximate total	11,000	190,000,000

Oceania

Australia	....	620,000
New Zealand	45,000	3,800,000
Philippine Islands	....	1,150,000
Sumatra	11,600	2,000,000
Java	56,500	500,000
Borneo	....	2,500,000
New Guinea	....	5,000,000
Tasmania	34,500	400,000
Celebes	....	1,000,000
Approximate total	147,000	17,000,000

TABLE II

LAND AND WATER, AND POPULATION OF THE STATES OF THE UNITED STATES

State or Territory.	Square Miles.			Population 1920.
	Gross Area.	Water.	Land.	
Alabama	52,250	710	51,540	2,348,174
Arizona	113,020	100	112,920	324,162
Arkansas	53,850	805	53,045	1,752,204
California	158,360	2,380	155,980	3,420,861
Colorado	103,925	280	103,645	939,629
Connecticut	4,990	145	4,845	1,380,631
Delaware	2,050	90	1,960	223,003
District of Columbia	70	10	60	437,571
Florida	58,680	4,440	54,240	968,470
Georgia	59,475	495	58,980	2,895,832
Idaho	84,800	510	84,290	431,866
Illinois	56,650	650	56,000	6,485,280
Indiana	36,350	440	35,910	2,930,390
Iowa	56,025	550	55,475	2,404,021
Kansas	82,080	380	81,700	1,769,257
Kentucky	40,400	400	40,000	2,416,630
Louisiana	48,720	3,300	45,420	1,798,509
Maine	33,040	3,145	29,895	768,014
Maryland	12,210	2,350	9,860	1,449,661
Massachusetts	8,315	275	9,040	3,852,356
Michigan	58,915	1,485	57,430	3,668,412
Minnesota	83,365	4,160	79,205	2,387,125
Mississippi	46,810	470	46,340	1,790,618
Missouri	69,415	680	68,735	3,404,055
Montana	146,080	770	145,310	548,889
Nebraska	77,510	670	76,840	1,296,372
Nevada	110,700	960	109,740	77,407
New Hampshire	9,305	300	9,005	443,083
New Jersey	7,815	290	7,525	3,155,900
New Mexico	122,580	120	122,460	360,350
New York	49,170	1,550	47,620	10,385,227
North Carolina	52,250	3,670	48,580	2,559,123
North Dakota	70,795	600	70,195	646,872
Ohio	41,060	300	40,760	5,759,394
Oklahoma	70,430	600	69,830	2,028,283
Oregon	96,030	1,470	94,560	783,389
Pennsylvania	45,215	230	44,985	8,720,017
Rhode Island	1,250	197	1,053	604,397
South Carolina	30,570	400	30,170	1,683,724
South Dakota	77,650	800	76,850	636,547
Tennessee	42,050	300	41,750	2,337,885
Texas	265,780	3,490	262,290	4,663,228
Utah	84,970	2,780	82,190	449,396
Vermont	9,565	430	9,135	352,428
Virginia	42,450	2,325	40,125	2,309,187
Washington	69,180	2,300	66,880	1,356,621
West Virginia	24,780	135	24,645	1,463,701
Wisconsin	56,040	1,590	54,450	2,632,067
Wyoming	97,890	315	97,575	194,402
Totals and averages	3,025,880	54,842	2,971,038	105,710,620

The above estimates of the potential horse-power represent continuous horse-power available at the ordinary low stages of streams. In a great many instances, they are entirely estimated from rainfall studies and topography. Thus, though the potential water power of the world is estimated at nearly 440 million horse-power when the streams are at ordinary low-water stage, and the present installed capacity at a little more than 23 million horse-power, or more than 5 per cent of the estimated potential power, probably not more than 2 or 3 per cent of the total potential power has been developed, and the extreme ultimate development, based on storage, may reach several billion horse-power.

CONSERVATION OF NATURAL FUEL RESOURCES

One of the most important questions of the present time is the one relating to the conservation of our natural fuel resources. While in 1880 the yearly coal consumption in this country was only approximately 70 million tons, in 1918 it amounted to about 675 million tons (Fig. 5). The output of our oil fields has, during the same time, also increased at the same astonishing rate, while the growth of our population during this period was only about 85 per cent, or about one-seventh the rate at which the fuel consumption increased. It is easy to realize what a tremendous drain this consumption has been on our natural fuel resources, and in justice to the welfare of the nation and of coming generations every practicable means should be employed for reducing it.

A material saving has been effected by the introduction of more efficient apparatus and improved systems of operation. In the modern central station, very great economies have resulted from the substitution of a few large and highly efficient boilers and steam turbines for a large number of relatively small and uneconomical units, and from the introduction of economy and skill not attainable in the smaller plants. The direct application of the power to the work through electric motors, replacing indirect application through inefficient countershafting and belting, has also resulted in a very material increase in economy.

Beyond the above gains, which may be considered well within the limits of possible attainment by our present knowledge, it is reasonable to assume that the efficiency of our fuel engines will not be increased very materially in the near future. The only safe method of reducing the consumption of our natural fuel resources is to utilize the enormous energy of the numerous water powers, which is now going to waste.

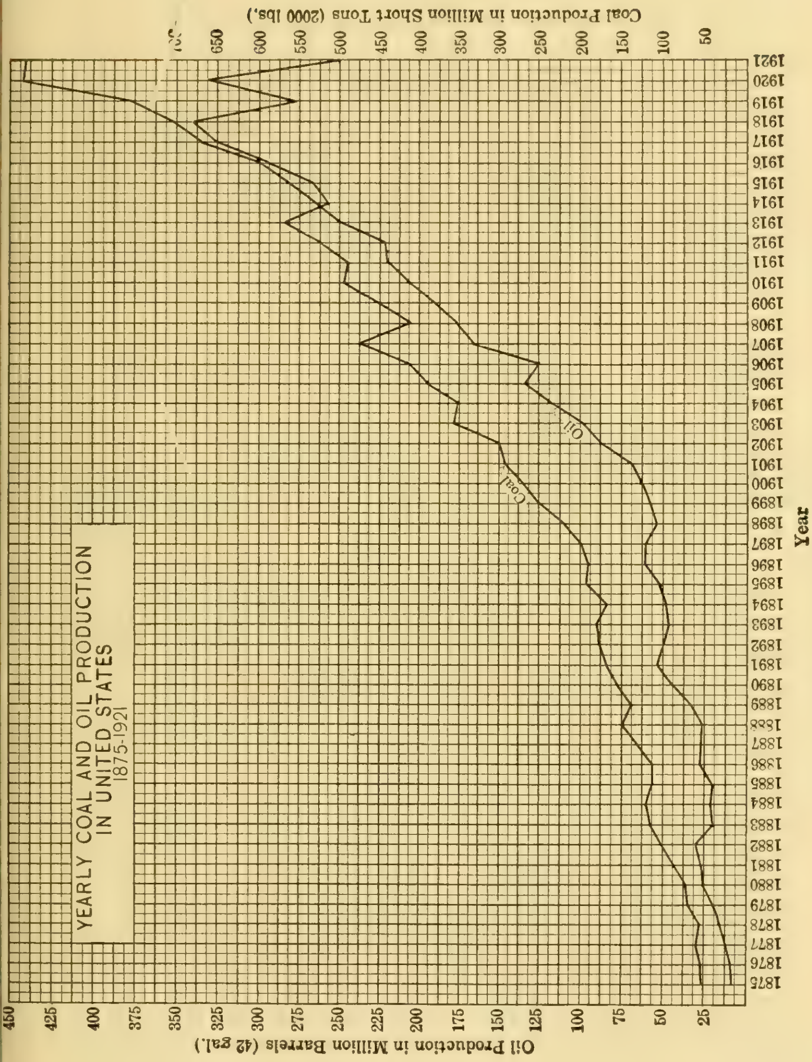


FIG. 5.—Yearly Coal and Oil Production in United States

According to the Census Report, the developed water powers of this country may be taken as approximately 9 million horse-power. Assuming that one hydraulic horse-power corresponds to an annual coal consumption of 8 tons, it follows that the utilization of this water power means a yearly saving in the coal consumption of 72 million tons.

In the recent Geological Survey Report, the minimum water power in this country which can be readily developed is placed at 28 million horse-power. This enormous power, which is now entirely wasted, could, if developed, effect a yearly saving of 250 million tons of coal, besides releasing about 750,000 men for other work, and in addition dispense with the tremendous railroad equipment required for its transportation.

AVAILABLE AND DEVELOPED WATER POWERS IN UNITED STATES

Table III, which follows, is also taken from the Geological Survey Report previously quoted. It gives the water power resources of the United States and the installed water-wheel capacity, wheels in plants of all sizes being included.

The basis on which the figures are estimated should be kept clearly in mind. The head was determined by dividing the rivers into sections of different lengths, the lengths depending on channel slope; and the fall and flow of each section were determined from the best available source of information. A conversion efficiency of 75 per cent was assumed, and no storage was considered. Thus, the minimum horse-power is that obtainable at minimum flow, and the maximum that obtainable with the flow available for 50 per cent of the time. The mean flow for each of the two lowest seven-day periods in each year was determined, and the mean of these two means, for the period of record, was taken as the minimum flow. The estimates for both minimum and maximum are conservative. In some of the New England States, complete development would probably require the installation of plant capacity equal to four times the estimated potential power at low water. The total capacity of possible water-power plants in the United States, estimated from similar developments, would be 112 million horse-power, of which now only about 8 per cent is developed.

The accompanying map, Fig. 6, shows the location of water-power developments and power sections of streams in the United States.

TABLE III

ESTIMATED POTENTIAL AND DEVELOPED WATER POWER IN UNITED STATES

State and Division.	Total Potential Water Power. Minimum. Horse-power.	Minimum. Per cent.	Maximum. Horse-power.	Maximum. Per cent.	Installed Capacity of Water Wheels. Horse-power.	Per cent.
New England:						
Maine	443,000	1.59	809,000	1.50	412,000	4.46
New Hampshire	135,000	.48	246,000	.46	217,000	2.35
Vermont	94,000	.33	172,000	.32	223,000	2.41
Massachusetts	118,000	.43	228,000	.42	330,000	3.57
Rhode Island	6,000	.02	13,000	.02	43,000	.46
Connecticut	72,000	.26	137,000	.26	156,000	1.69
Middle Atlantic division:						
New York	1,037,000	3.71	1,698,000	3.15	1,300,000	14.06
New Jersey	44,000	.16	106,000	.20	38,000	.41
Pennsylvania	276,000	.99	684,000	1.27	397,000	4.30
East North Central division:						
Ohio	59,000	.21	178,000	.33	54,000	.58
Indiana	43,000	.16	118,000	.22	29,000	.31
Illinois	192,000	.69	345,000	.64	84,000	.91
Michigan	180,000	.64	293,000	.54	327,000	3.54
Wisconsin	358,000	1.28	670,000	1.24	318,000	3.44
West North Central division:						
Minnesota	232,000	.83	494,000	.92	224,000	2.42
Iowa	160,000	.57	382,000	.71	192,000	2.08
Missouri	72,000	.26	163,000	.30	27,000	.29
North Dakota	88,000	.31	207,000	.38	400	.00
South Dakota	43,000	.16	75,000	.14	18,000	.19
Nebraska	196,000	.70	366,000	.68	18,000	.19
Kansas	111,000	.40	269,000	.50	24,000	.26
South Atlantic division:						
Delaware	5,000	.02	11,000	.02	8,000	.09
Maryland and Dist. of Col.	48,000	.17	133,000	.25	20,000	.22
Virginia	492,000	1.76	870,000	1.62	157,000	1.70
West Virginia	381,000	1.36	1,051,000	1.95	20,500	.22
North Carolina	578,000	2.07	875,000	1.62	370,000	3.94
South Carolina	460,000	1.64	677,000	1.26	453,000	4.90
Georgia	374,000	1.34	627,000	1.16	342,000	3.70
Florida	8,000	.03	13,000	.02	11,000	.12
East South Central division:						
Kentucky	83,000	.30	197,000	.37	14,000	.15
Tennessee	463,000	1.66	761,000	1.41	222,000	2.40
Alabama	509,000	1.82	943,000	1.74	260,000	2.81
Mississippi	32,000	.11	63,000	.12	8,500	.09
West South Central division:						
Arkansas	22,000	.08	61,000	.11	6,100	.07
Louisiana	1,000	.00	2,000	.00	4,000	.04
Oklahoma	75,000	0.27	208,000	0.39	4,600	.05
Texas	255,000	.91	551,000	1.02	11,000	.12
Mountain division:						
Montana	2,749,000	9.84	4,331,000	8.03	420,000	4.54
Idaho	2,362,000	8.45	5,067,000	9.40	243,000	2.63
Wyoming	773,000	2.76	1,305,000	2.42	6,600	.07
Colorado	842,000	3.01	1,697,000	3.15	133,000	1.54
New Mexico	160,000	.57	439,000	.81	3,000	.03
Arizona	893,000	3.20	1,698,000	3.15	52,000	.56
Utah	743,000	2.66	1,318,000	2.45	122,000	1.32
Nevada	172,000	.62	276,000	.51	27,000	.29
Pacific division:						
Washington	4,932,000	17.65	8,647,000	16.04	487,000	5.27
Oregon	3,148,000	11.27	6,613,000	12.27	295,000	3.19
California	3,424,000	12.25	7,818,000	14.50	1,111,000	12.02
Summary:						
New England	868,000	3.11	1,605,000	2.98	1,381,000	14.94
Middle Atlantic division	1,357,000	4.86	2,488,000	4.62	1,735,000	18.77
East North Central division	832,000	2.98	1,604,000	2.98	812,000	8.78
West North Central division	902,000	3.23	1,956,000	3.63	503,400	5.43
South Atlantic division	2,346,000	8.39	4,257,000	7.90	1,381,500	14.89
East South Central division	1,087,000	3.89	1,964,000	3.64	504,500	5.45
West South Central division	353,000	1.26	822,000	1.52	25,700	.28
Mountain division	8,694,000	31.11	16,131,000	29.92	1,006,600	10.98
Pacific division	11,504,000	41.17	23,078,000	42.81	1,893,000	20.48
United States	27,943,000	100.00	53,905,000	100.00	9,242,700	100.00

FIG. 6.—Location of Water Powers in United States.

PRIMARY POWER AND ITS USES

An estimate, based on Government reports, of the capacity of all stationary prime movers in the United States, for central stations, manufacturers, electric railways, etc., is given in the following table:

TABLE IV

CAPACITY OF STATIONARY PRIME MOVERS IN THE UNITED STATES

Year.	Horse-power		Percentage of Water Power.
	Total.	Water Power.	
1900	17,500,000	3,300,000	18.8
1902	19,500,000	3,700,000	19.0
1904	22,500,000	4,100,000	18.2
1906	25,500,000	4,700,000	18.4
1908	29,000,000	5,360,000	18.5
1910	32,500,000	6,000,000	18.4
1912	36,000,000	6,700,000	18.6
1914	38,500,000	7,400,000	19.2
1916	42,000,000	8,200,000	19.5
1918	45,000,000	8,800,000	19.5
1920	49,000,000	9,500,000	19.4

Forty years ago (1882) electric central station service began in the United States, the two plants installed that year being the Pearl Street Steam Station in New York City and the small hydro-electric station at Appleton, Wisconsin. The total generating capacity of these stations was not more than about 600 kw., while in 1920 the total generating capacity of the central station plants in the United States was 14½ million kilowatts and the energy generated over 39 billion kilowatt hours. Due to the industrial depression the amount of energy generated in 1921 was reduced to approximately 37 billion kilowatt hours.

Three-quarters of this growth in the amount of energy generated has accrued during the last ten years, as shown in Table V, which also shows the energy distribution for lighting, industrial power, and electric railways, as well as the line losses and inter-company business. Table VI gives the installed generator and prime-mover capacity and the energy output and its distribution in per cent.

A study of these recent figures discloses many interesting facts. For example, while the population of the United States has only increased about 15 per cent in the years 1910–20, the number of customers served by electric central stations has increased more than 250 per cent, and

TABLE V

Estimated Electrical Energy Generation and Distribution by Electric Central Stations in United States, 1882 to 1922

Year.	Total Energy Generated, kw.-hrs.	Losses, kw.-hrs.	Distribution of Energy.		
			Lighting, kw.-hrs.	Industrial Power, kw.-hrs.	Electric Railways, kw.-hrs.
1887	175,000,000	44,000,000	120,000,000	11,000,000	0
1892	300,000,000	75,000,000	190,000,000	30,000,000	5,000,000
1897	800,000,000	250,000,000	485,000,000	50,000,000	15,000,000
1902	2,337,051,000	650,000,000	985,000,000	602,051,000	100,000,000
1907	5,861,000,000	1,331,000,000	1,870,000,000	1,500,000,000	1,160,000,000
1912	11,569,358,000	2,546,000,000	2,752,000,000	3,254,000,000	3,017,358,000
1914	14,400,000,000	2,968,000,000	3,732,000,000	4,061,000,000	3,639,000,000
1915	16,175,000,000	3,000,000,000	4,100,000,000	5,175,000,000	3,900,000,000
1916	21,230,000,000	4,205,000,000	4,900,000,000	7,564,000,000	4,561,000,000
1917	25,438,433,000	5,292,085,000	5,600,000,000	9,599,000,000	4,947,348,000
1918	29,880,000,000	5,720,000,000	5,700,000,000	13,500,000,000	4,960,000,000
1919	35,028,900,000	6,010,000,000	6,200,000,000	17,838,900,000	4,980,000,000
1920	39,199,392,000	7,185,000,000	6,870,000,000	20,154,392,000	4,990,000,000
1921	36,878,055,000	6,780,000,000	7,400,000,000	17,698,055,000	5,000,000,000

By permission of *Electrical World.*

TABLE VI

Installed Generator and Prime Mover Capacities and Energy Output of Electric Central Stations in United States

	1912.	1917.	1920.	1921.
Total installed generator capacity, kw.	5,165,400	8,994,400	12,760,900	14,466,900
Total installed prime mover capacity, H.P.	7,530,000	12,936,700	17,061,000	19,737,500
Steam, H.P.	4,949,800	8,439,000	11,476,000	13,332,000
Water, H.P.	2,469,200	4,277,300	5,377,400	6,200,300
Oil and gas, H.P.	111,000	220,400	207,500	205,200
Total kw. hours generated	11,569,358,000	25,438,433,000	39,199,392,000	36,878,055,000
Per cent by fuel power	49.5	47.3	62.9	63.5
Per cent by water	50.5	54.7	37.1	36.5
Lighting load, per cent of total	23.8	22.0	17.5	20.0
Industrial power load, per cent of total	28.2	37.6	51.5	48.0
Electric railway load, per cent of total	26.0	19.6	12.7	13.6
Losses and inter-company business, per cent of total	22.0	20.8	18.3	18.4

the amount of electric energy sold more than 350 per cent. It is also interesting to note the great increase in the power sold for industrial purposes, the percentage having increased from 28 per cent in 1912 to over 51 per cent in 1920. The proportion of the total energy generated by water power has decreased considerably, the reason for this, of course, being the tremendous increase in the building of steam power stations during the later part of the war and shortly thereafter. The acute power situation at that time demanded that the plants be completed in the shortest time possible, and it takes a much longer time to build a hydroelectric plant, with its dam, headworks, etc., than to build a steam-power plant.

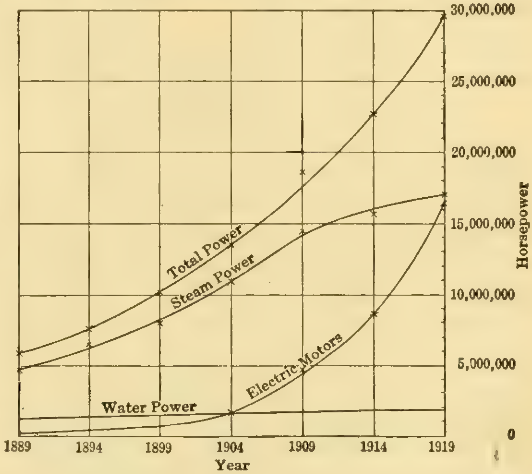


FIG. 7.—Relation between Primary Power and Electric Motors in the Manufacturing Industry.

Table VII shows, for all manufacturing industries combined, the total power, steam and water primary power, as well as purchased power and electric motors installed for the period 1909–1919. The relative increase is represented by the curves in Fig. 7, which show the rapid increase in the use of electric motor drive. Another interesting point, also brought out by these curves, is the lesser increase of installed primary power as compared to the total power, the difference naturally being due to the increase in purchased power from central stations. This is also confirmed by a very extensive investigation of the industrial load of the United States, recently completed by the *Electrical World*. No less than eighty-five thousand questionnaires were sent out, and over twelve thousand companies rendered complete data as to the use of electric energy, etc., in their respective plants. These very interesting and valuable data, contained in the *Electrical World* for Jan. 6, 1923, show that of the nearly 30 billions of kilowatt-hours of electric energy consumed in the manufacturing industries of the country during 1920, about 57 per cent was purchased from public utility companies, as compared to 43 per cent generated in private plants.

TABLE VII

Power Used in Manufacturing Industries in the United States

	1909.	1914.	1919.*
Total aggregate horse-power	18,675,376	22,547,574	29,504,792
Total primary power, H.P	16,802,706	18,500,036	20,062,636
Steam, H.P.	14,228,632	15,681,688	17,037,973
Water, H.P	1,822,888	1,826,443	1,765,263
Gas and oil, H.P	751,186	991,905	1,259,400
Purchase power, H.P	1,872,670	4,047,538	9,442,156
Electric motors used, H.P	4,817,140	8,847,622	16,317,277

* Preliminary Census Report; subject to correction.

Table VIII gives the aggregate power requirements and the horse-power capacity of electric motors used in some of the leading manufacturing industries. The aggregate horse-power required per $1000 value of product, and per person engaged in the particular industry, is given in Table IX.

TABLE VIII

Power and Electric Motors in Leading Manufacturing Industries in the United States

	1909.		1914.		1919.	
	Total Power, H.P.	Electric Motors, H.P.	Total Power, H.P.	Electric Motors, H.P.	Total Power, H.P.	Electric Motors, H.P.
Agricultural implements	100,601	38,905	121,428	83,117	128,249	100,263
Automobile factories	75,550	41,829	173,684	135,818	544,242	490,560
Cars and steam railroad repair shops	293,361	161,288	433,994	325,054	594,515	500,141
Cement	371,799	158,749	490,402	336,516	488,808	345,535
Cotton goods	1,296,517	235,902	1,585,953	512,903	1,840,201	861,609
Electric machinery	158,768	164,540	227,731	262,119	438,839	479,366
Foundry and machine shops	869,305	623,914	1,129,768	896,849	1,054,840	953,795
Iron and steel—Blast furnaces	1,173,422	135,143	1,222,273	212,582	1,581,432	242,554
Iron and steel—Rolling mills	2,100,978	716,609	2,706,553	1,207,715	3,820,917	2,350,596
Lumber and timber	2,840,082	130,707	2,796,902	306,540	2,358,937	279,478
Paper and wood pulp	1,304,265	130,120	1,621,154	325,211	1,851,014	583,586
Printing and publishing	297,763	229,312	335,210	283,206	326,956	297,149

TABLE IX

POWER USED IN LEADING MANUFACTURING INDUSTRIES IN THE UNITED STATES

	1909.		1914.		1919.	
	H.P. per $1000 Value of Product.	H.P. per Person Engaged in Industry.	H.P. per $1000 Value of Product.	H.P. per Person Engaged in Industry.	H.P. per $1000 Value of Product.	H.P. per Person Engaged in Industry.
Agricultural implements	0.69	1.67	0.74	2.09	0.42	1.92
Automobile factories	0.30	0.89	0.29	1.19	0.17	1.38
Cars and steam railroad shops	0.72	0.98	0.85	1.20	0.47	1.15
Cement	5.90	12.60	4.84	15.40	2.78	16.10
Cotton goods	2.07	3.35	2.34	3.93	0.87	4 14
Electric machinery	0.72	1.50	0.68	1 58	0.44	1.62
Foundry and machine shops	0.71	1.41	1.30	1.69	0.46	1.86
Iron and steel—Blast furnaces	3.00	27.30	3.86	37.00	2.00	33.70
Iron and steel—Rolling mills	2 13	8.10	2.95	9.85	1.35	9.05
Lumber and timber	2.46	3.62	3.90	4.00	1 70	4.65
Paper and wood pulp	4.88	16 05	4.90	16 90	2.35	14.85
Printing and publishing	0.45	0 77	0.41	0 80	0 21	0.88

Table X gives the Census figures of total aggregate horse-power used in mines and quarries; also the horse-power of prime movers of various kinds and of purchased power, chiefly used for motor drive. It also shows how the horse-power used per person has materially increased, showing the increased use of power applications to offset the shortage and increased cost of labor. The reduced value of horse-power used per value of product is naturally due to the greatly increased values caused by the war.

TABLE X

POWER USED IN ALL MINES AND QUARRIES IN THE UNITED STATES

	1902.	1909.	1919.
Total aggregate horse-power	2,867,562	4,699,910	6,786,475
Total primary power, H.P	2,753,555	4,483,807	5,147,613
Steam, H.P	2,432,963	3,840,923	3,733,391
Water, H.P	60,897	114,620	41.524
Gas and oil, H.P	259,695	528,264	1,372,698
Purchase power, H.P	114,007	216,103	1,638,862
Electric motors used, H.P	Figures not available	723,727	2,890,046
Horse-power required per $1000 value of product	3.6	4.0	2.15
Horse-power used per person engaged in industry	4.62	3.82	6.25

Table XI gives the statistics relating to the power used by electric railways. In this case, almost the entire primary power output is, of course, converted to electric power.

TABLE XI

POWER USED BY ELECTRIC RAILWAYS IN THE UNITED STATES

	1907.	1912.	1917.
Total primary power, H.P.	2,519,823	3,661,385	4,200,192
Steam, H.P.	2,411,527	3,165,888	3,543,915
Water, H.P.	91,961	471,307	627,983
Gas and oil, H.P.	16,335	24,190	28,294
Total kw. hrs. generated	4,759,130,000	6,002,659,000	7,240,506,000
Total kw. hrs. purchased	1,160,000,000	3,017,358,000	4,947,348,000

COMMERCIAL OPPORTUNITIES FOR HYDRO-ELECTRIC POWER

During recent years there has been a very large increase in the number and variety of electric power applications, and this has a very important bearing in stimulating the development of water powers. Among the more important industries affected may be mentioned: Agricultural work, including irrigation, textile mills, mining, electro-chemical work, railroad electrifications, etc.

Agricultural Work. The possibilities of the use of hydro-electric power in connection with farming and agricultural work are many, and offer one of the most promising fields of the future. The unqualified success of electric power in this line of work makes it a factor of such importance that it must now be seriously considered as affecting both the cost and quality of the products of the modern farm. Compared to other forms of applied power, the chief advantages of electricity are reliability, safety, cleanliness and flexibility in application. Power can be readily and economically distributed to the scattered location of the various buildings, where the cost of providing separate engines would be practically prohibitive. Fire risk is reduced to a minimum, which is of greatest importance on isolated farms, where fire-fighting appliances are limited (Fig. 8). With a number of motors installed for the various classes of service, the operating periods can be so arranged as to secure a very good load-factor, thus minimizing the cost of power.

The power supply may be obtained from the extensive net-works of high-tension transmission lines which are now being erected in so

many sections of the country, and which are continually being extended at a very rapid rate. While this supply, without doubt, offers the simplest and cheapest source of power, there are thousands of small streams whose wasted energy might readily be transformed and applied to useful work on farms, by the installation of small and inexpensive water-power plants.

Table XII shows some of the more important applications of electric drive for farm machinery and power required.

Irrigation. Water is a necessity for the growth of every crop. In the Western States, the rainfall is, as a rule, insufficient to support even

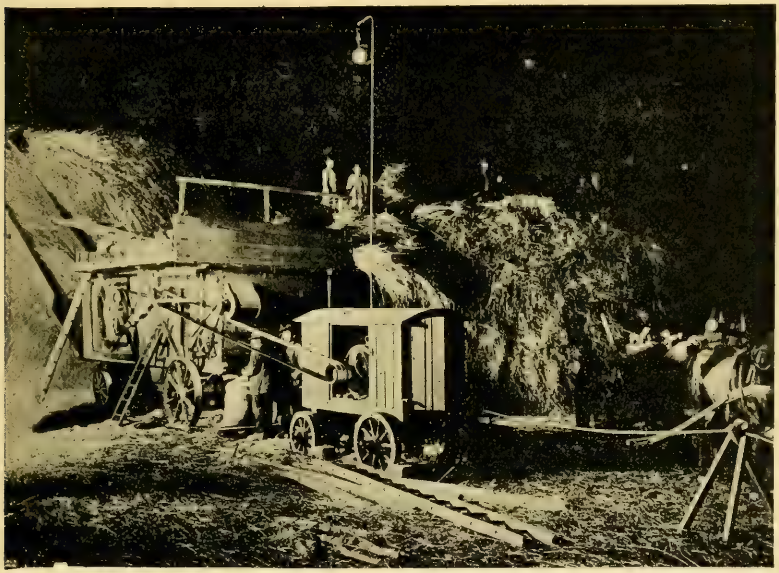


FIG. 8.—Operating Thresher at Night with Portable Motor Outfit.

a scant growth of vegetation, but in the Central and Eastern States the average rainfall during the growing season is ordinarily considered sufficient. However, in the latter sections of the country hardly a year passes without some particular section being badly in need of rain.

As rains, to be beneficial, must come at such times and in such amounts as will properly moisten the soil and produce growth; a check in this supply of soil moisture at any stage of the growth affects both the quality and quantity of the yield and may greatly reduce the profits of the grower. The real test of the necessity of irrigation is not the total annual rainfall, but the monthly, and, in the case of most crops, the weekly amount of precipitation throughout the growing

season. Under average conditions, it is safe to say that a drought occurs whenever the rainfall totals less than one inch in any fifteen-day period; and crops will usually suffer if they do not receive more than this amount of rain, especially during the spring and early summer months.

TABLE XII

MOTORS FOR FARM MACHINERY

Machines.	Horse-power of Motor.		
	Minimum.	Maximum.	Size Most Commonly Used on Average Farms.
Feed grinders (small)	3	10	5
Feed grinders (large)	10	30	15
Ensilage cutters	10	25	15–20
Shredders and huskers	10	20	15
Threshers, 19-inch cylinder	12	18	15
Threshers, 32-inch cylinder	30	50	40
Corn shellers, single hole	¾	1½	1
Power shellers	10	15	15
Fanning mills	....	....	¼
Grain graders	....	....	¼
Grain elevators	1½	5	3
Concrete mixers	2	10	5
Groomer, vacuum system	1	3	2
Groomer, revolving system	1	2	1
Hay hoists	3	15	5
Root cutters	1	5	2
Cord wood saws	3	10	5
Wood splitters	1	4	2
Hay balers	3	10	7½
Oat crushers	2	10	5

Professor F. H. King, in his book on irrigation and drainage, furnishes the data given in Table XIII as the highest probable duty of per water acre for different yields of different crops.

Some artificial means of supplying water to the land is therefore a necessity in the western section of the country, and would be excellent insurance to the central and eastern parts as well.

Two general methods of supplying this water are now in use: the ordinary gravity flow, in which water is taken from a reservoir or ditch; and the mechanical lift, in which it is pumped from a well, pond, river

or lake. Of the two, the mechanical lift has had a far more rapid development. There are two reasons for this: first, because the land which can be economically irrigated by the gravity method has been practically all taken up; and, second, because the farmer can pump water to almost any elevation, and in this way he is enabled to irrigate land which is above his source of water supply. This is impossible when the gravity system is used.

TABLE XIII

Duty of Water for Different Crops

Bushels per acre	15	20	30	40	50	60
	Least Number of Acre-inches of Water.					
Wheat	4.5	6.0	9.0	12.0	15.0	18.0
Barley	3.2	4.3	6.4	8.5	10.7	12.8
Oats	2.3	3.1	5.7	6.3	7.8	9.4
Maize (corn)	2.5	3.3	5.0	6.7	8.4	10.0
Potatoes	.....	0.4	0.6	0.8	1.0	1.2
Tons per Acre	1	2	3	4	6	8
Clover hay	4.4	8.8	13.3	17.7	26.5	35.0
Corn (green)	2.1	4.2	6.2	8.3	12.5	16.6

Irrigation pumping, from the farmer's point of view, has many advantages, in that a pumping plant will give him water just at the time he wants it; this is a more important factor to him than the saving of money effected. It is only in exceptional cases that water can be gotten from a ditch just at the time when it is wanted, as ditch riders and water superintendents must serve all alike. Not only this, but when water is turned into a ditch, it must run in quantities in order to secure economy; and it is not possible that every man along a ditch will be similarly situated with regard to the progress of his work, so that all will require water at any one time.

If water is to be pumped, some kind of power is necessary to operate the pump. Among the more important sources of power are the gasoline engine, steam engine, and electric motor. The electric motor, however, is rapidly displacing the other two wherever electric power is available, just as it has already done in the city. The principal advantage of the electric motor is that its power is instantaneously available

and it will always run when wanted. Furthermore, it can be run for months at a time without shutting down the plant, and there are thousands of electric pumping installations in the Far West which run twenty-four hours a day for six months at a time; this is entirely feasible, as the only attendance that is required for electrical equipment is an occasional oiling of the motor bearings. The steam engine, on the other hand, requires the constant attendance of a licensed engineer, while the gasoline engine has a large number of moving parts, which must necessarily be adjusted from time to time. It is practically impossible to operate a gasoline engine for six months at a time without extensive repairs at the end of the period. The ability of the electric motor to run all the time is, therefore, a distinct advantage, in that a small reservoir can be used to store the water pumped during the night, and in this way a much smaller equipment can be used than would otherwise be required. The electric motor has the added advantage of remote control, the farmer being able to stop and start it even if he is several miles away.

The advantages of electric power for irrigation purposes have been clearly demonstrated by the excellent work which is being done by the United States Reclamation Service, the United States Indian Service, and numerous cooperative and individual enterprises. In connection with these projects, electricity plays an important part. Hydro-electric power is generated on the nearest available river and the energy is transmitted over high-tension transmission lines to pumping stations scattered over the territory to be irrigated. Besides these, there are numerous other projects where hydro-electric power is similarly used for irrigating the land.

Mining. The advantage of using electric power for mining operations is now fully recognized, almost all new mines being equipped for electric drive, and a very large number of old ones changing over to this system. Not only does this reduce the cost of working, but it also offers a much safer and more reliable operation. The economy of electric-power distribution to the various points in a mine surpasses that of all other methods. The electric system eliminates long and expensive steam and air lines, with which the danger of breakdown and the difficulty of keeping up the necessary working pressure increase with every extension of the service. Electric distribution, on the other hand, is most simple and flexible. Very large districts can be efficiently supplied, and additions or alterations can at all times be made without the least difficulty.

A most efficient application of motors to the many forms of mining machines is readily accomplished. They can be direct connected, or

geared to the driving shafts, thus reducing the friction losses and repair charges to a considerable extent, while the cost of belting and countershafts is entirely eliminated. Individual motors can be substituted for driving conveyors, scrapers and other machinery in breakers and tipples, which formerly were equipped for group operation by means of inefficient engines. In motor-driven breakers, the saving in belting alone is considerable.

Operation with the electric system is very simple, and results in a material increase in the output of a mine. Perfect control is at all times possible. Simple, automatic, safety devices can be installed, and indicating or recording meters can be provided in the several circuits as desired, and the performance of every individual machine ascertained. This is a very important point, as it is possible to maintain the machinery in the best possible condition. Any excess consumption of power can at once be detected and the defect remedied, while an accurate record can be kept of the cost of the different operations.

Power may be purchased from nearby existing hydro-electric transmission companies, or available water powers may be developed and the energy transmitted to the mines. That water powers may, in some instances, compete with very cheap steam power is also illustrated by the system of the Appalachian Power Company, which furnishes a considerable amount of power from its hydro-electric plants on the New River in Virginia to the Pocahontas coal fields, a distance of about 50 miles.

The power required for mining operations naturally varies greatly, depending on the nature of the mine and the conditions. For anthracite coal mining, where the necessary pumping may account for nearly half of the power requirements, it may be as high as $17\frac{1}{2}$ kw. hrs. per ton of coal hoisted. For mines requiring less pumping, it may not be as much.

Electro-chemical Industries. The industrial processes founded upon electro-chemistry have a large and important part in the manufacture of a very wide range of commercial products, such as fertilizers, explosives, paper, wood pulp and numerous electro-chemicals, among which may be mentioned aluminum, carborundum, alundum, silicon, graphite, calcium carbide, cyanamid, ferro-silicon, ferro-chromium, ferro-manganese, caustic soda, sodium, chlorine, chlorate, chloroform, carbon tetrachloride, etc.

The question of cheap water power is vital in connection with electro-chemical industries; on the other hand, the location of raw materials and the facilities for transporting the product to the market

centers is also of the greatest importance, and this latter consideration has, to a great extent, hindered the development of our western water powers for electro-chemical products. Niagara Falls, on the other hand, forms an ideal example of what cheap water power has done for this industry. At this point are now situated the greatest electro-chemical industries in the world, not one of which was in existence when the Niagara Falls Power Company began to take water from the Niagara River to generate electricity. The expansion of these industries has been so rapid that, regardless of the expansion of the Niagara power plants, there has always been a shortage of power, and industries have had to seek other localities where power could readily be obtained.

Another great need for the immediate development of additional water power is the necessity of increasing our fertilizer supply and making it independent of foreign deposits. Phosphorus and nitrogen in available forms are the most important constituents of plant food and nitrogen is absolutely indispensable in the manufacture of explosives. Europe uses 200 pounds of fertilizer per acre of cultivated land; the United States uses 28 pounds. In twenty years, Germany, by the use of fertilizers, has increased the average yield of all crops grown three and one-half times as much per acre as America has done, the yield per acre in bushels for various crops being as follows:

TABLE XIV

CROP YIELDS

	Wheat.	Oats.	Barley.	Rye.	Potatoes.
Europe	32	47	38	30	158
United States	15	29	25	16	96

As a measure of preparedness, our reserve stock of nitrates is insignificant; and our nation would be powerless if our navy were not strong enough to protect our import from Chile. Fortunately, nitrates can readily be extracted from the atmosphere and fixed as a compound, by the utilization of electric energy. The possibilities of this process have never been more clearly demonstrated than during the World War, when Germany's entire supply was obtained in this way. In Norway, with its cheap water powers, the industry has long been established, about 350,000 horse-power being at present utilized, by one company alone, for the fixation of nitrogen. Figure 9 shows one of this company's power-houses and electric furnace building, with a capacity of 120,000 horse-power.

The power requirement varies widely for the different electrochemical products, as seen from Table XV, and in many instances it is a large item in the cost sheet of the product.

Railroad Electrification. Hydro-electric power will undoubtedly play an important part in connection with future railroad electrifica-

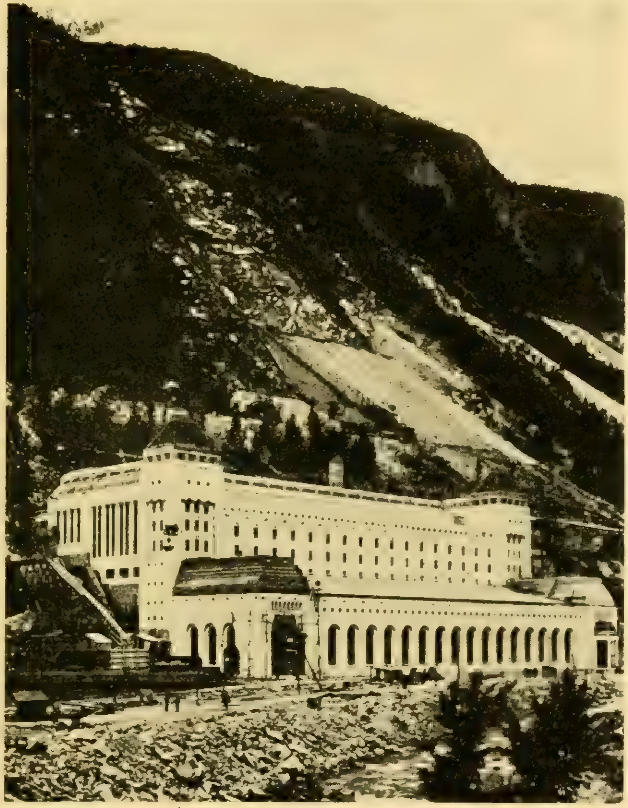


FIG. 9.—Rjukan II Power and Furnace House for Nitrogen Fixation in Norway. Capacity 120,000 horse-power.

tions, especially in the mountainous western states. Six hundred and forty-seven miles of the main line of the Chicago, Milwaukee & St. Paul Railroad have now been equipped for operation by electricity, power being supplied by nearby hydro-electric developments. In view of the economic success of this electrification, it is almost certain that within the next few years a majority of the railroads operating through the mountainous country of the Far West, where hydro-electric power

can be developed cheaply, will adopt electricity as a motive power. Several Eastern and Southern railroads are also contemplating electrification in the near future, and a large number of foreign roads have already gone in for quite extensive electrification programmes.

TABLE XV

Power Consumption of Electro-chemical Processes

(Kw.-hrs. per Ton of 2000 Pounds)

Product.	Process.	kw.-hrs.
Aluminum	Electrolytic	30,000
Alundum	Electro-thermic	2,000
Barium oxide	Electro-thermic	1,200
Cadmium	Electrolytic	2,500
Calcium carbide	Electro-thermic	3,500
Calcium cyanamide	Electro-thermic	3,000
Carbon bisulphide	Electro-thermic	850
Carborundum	Electro-thermic	8,500
Caustic soda, 2000 pounds Chlorine, 1840 pounds	Electrolytic	3,000
Copper	Electrolytic refining	300
Copper	Electrolytic	2,600
Ferro-chromium (60%)	Electro-thermic	8,000
Ferro-manganese (76%)	Electro-thermic	5,000
Ferro-molybdenum (60%)	Electro-thermic	8,400
Ferro-silicon (50%)	Electro-thermic	5,000
Ferro-silicon (75%)	Electro-thermic	10,000
Ferro-tungsten (70%)	Electro-thermic	7,600
Ferro-uranium (40%)	Electro-thermic	8,000
Ferro-vanadium (35%)	Electro-thermic	6,800
Graphite	Electro-thermic	7,800
Hydrogen, 1000 cubic feet Oxygen, 500 cubic feet	Electrolytic	150
Iron	Electro-thermic	2,500
Iron	Electrolytic	4,000
Lead	Electrolytic refining	145
Magnesium	Electrolytic	27,000
Nitric acid	Electro-thermic	17,500
Phosphorus	Electro-thermic	12,000
Potassium chlorate	Electrolytic	1,350
Sodium	Electrolytic	20,000
Sodium chlorate	Electrolytic	7,000
Tin	Electrolytic refining	175
Zinc	Electrolytic	4,000

Among the many reasons that may justify a change in motive power from steam to electricity on main line railroads, are freedom from smoke

and cinders, increased carrying capacity of track, decreased expense of operation, elimination of delays due to grades and other conditions, increased safety and reliability, etc. When we realize that 25 per cent of the coal mined in the United States is used for the railroads and that the steam locomotive does not utilize this coal efficiently, it is at once obvious that a saving in the coal consumption of the country could be accomplished by an increased electrification of our steam railroads.

CLASSIFICATION OF DEVELOPMENTS

Water-power developments may be roughly divided into two classes: first, low-head; and second, medium and high-head.

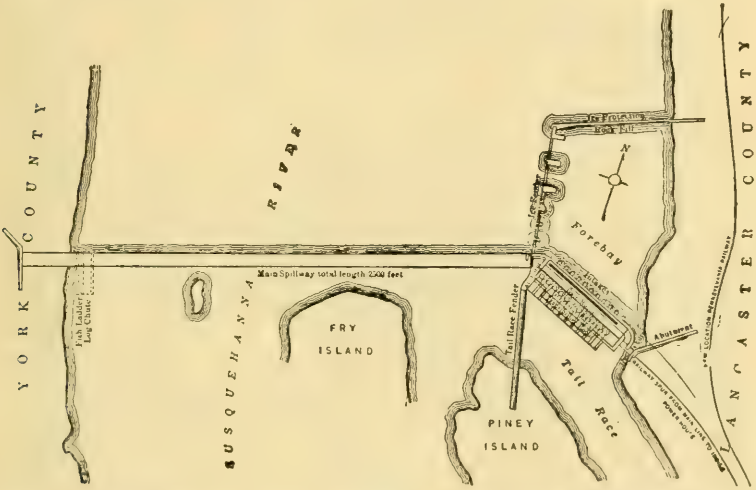


Fig. 10.—Map Showing General Lay-out of Pennsylvania Water and Power Companies, Development at Holtwood, Pa.

Low-head Developments. To this class belong plants consisting of a dam which creates pondage at the point where the water is to be utilized, so that the water passages to the turbine units will be comparatively short, while the quantity is large. The chief items comprising the headworks of such a development are, the dam with its spillway; the forebay, the intake, and the tailrace.

Typical plants of this kind are shown in Figs. 10 and 11. A dam extends across the river and impounds a large body of water above it. It is built with a spillway section for the entire length, this being necessary on account of the large flood discharges. The pondage may also be materially increased by placing flashboards on top of the dam, and by this means an additional head is also gained.

Precautions must always be taken to guard against floating logs, debris, ice, etc., and for this a wing dam, having submerged arches through which the water enters the forebay, has been built at right angles to the main dam, between which and a rock-fill above there are floating booms, serving to deflect such ice, etc., as may be carried towards the forebay. Care should be taken that the arches of the wing dam are submerged at least 2 feet when the water level is at its lowest.

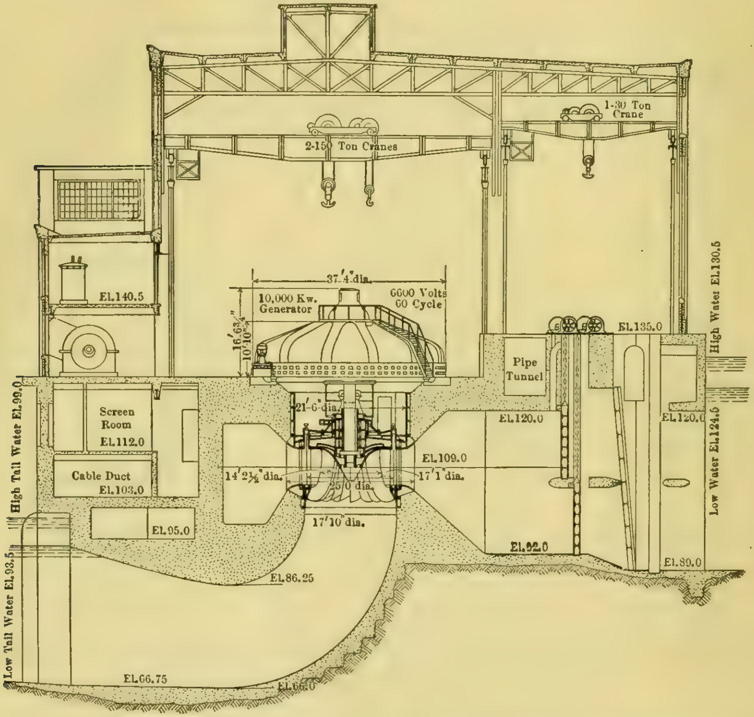


FIG. 11.—Sectional Elevation of Power House, Cedars Rapids Mfg. and Power Company.

Any ice which enters the forebay despite these safeguards, as well as ice which may be formed there, can be diverted by providing ice chutes from the forebay toward the tailrace. The crests of these should be of the same elevation as the crest of the main spillway.

Medium and High-head Developments. To this class belong those plants which consist of a diversion dam with an intake at the head-waters, whence the flow is led through tunnels, open canals, or flumes to a forebay pond. This is usually located on the hillside above the power-house, and pipe lines carry the water from the same to the tur-

bines. In other instances the entire water conductor from the diversion dam to the wheels may be of enclosed pressure type. The quantity of water is usually much smaller than in low-head plants.

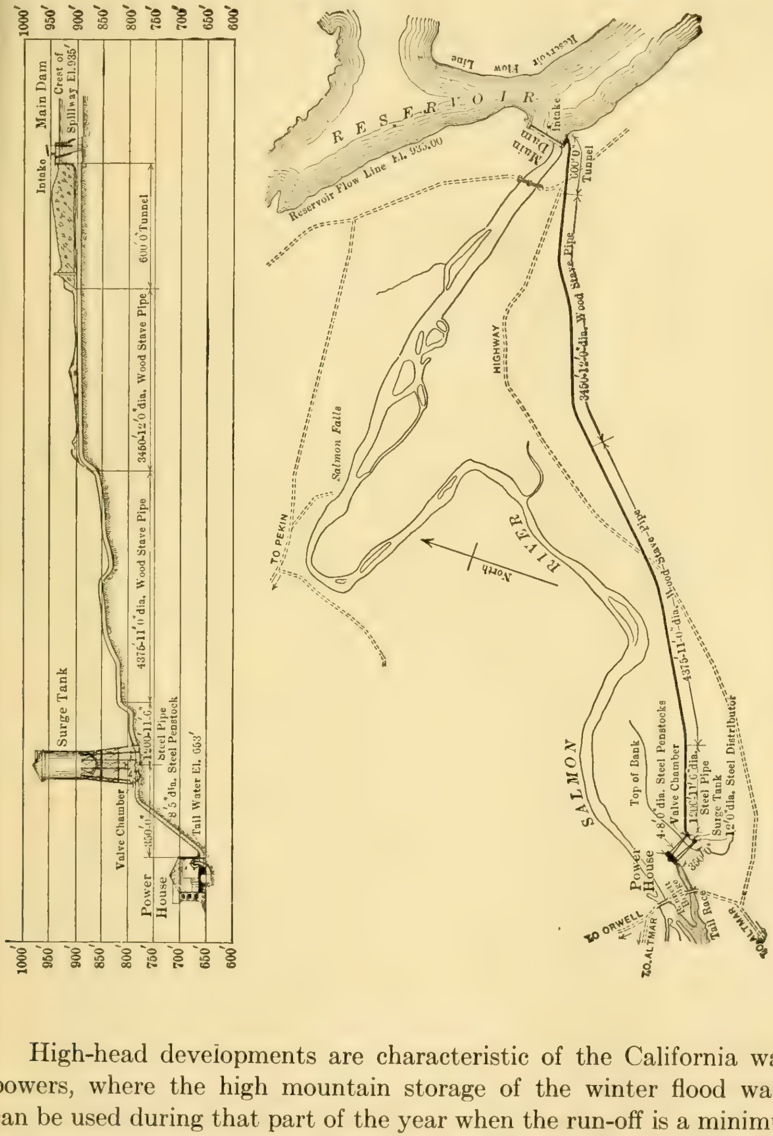


Fig. 12.—Salmon River Power Company's Development.

High-head developments are characteristic of the California water powers, where the high mountain storage of the winter flood waters can be used during that part of the year when the run-off is a minimum.

A typical medium-head installation is shown in Fig. 12. It consists of a diversion dam with spillway for impounding the waters of

the river, thus forming a reservoir of considerable size. The intake is located at right angles to the dam, thus lessening the accumulation of ice, logs, trees and other floating debris in front of the intake trash racks.

The water conductor connecting the intake and the turbines in the power-house consists of five sections: a reinforced concrete-lined tunnel blasted through rock; a wood-stave pipe; a steel pipe; a distributor; and finally, the steel penstocks.

CHAPTER II

HYDROLOGY

1. PROPERTIES OF WATER

Weight. The weight and specific gravity of water vary somewhat, depending on its temperature and on the various impurities which it contains in solution or carries in suspension. For pure water, the weight may be considered practically constant, as the maximum variation has been found to be only about 0.05 of 1 per cent. Its weight is now generally assumed to be 62.355 pounds per cubic foot at a temperature of 62° F., although authorities differ somewhat about the exact figure. Water of lakes and rivers will, under ordinary circumstances vary between 62.3 and 62.5 pounds, depending on the impurities. Table XVI, however, shows that a considerable variation may be expected under unusual conditions, as in the Great Salt Lake, where the water, because of the large amount of salt which it contains, weighs nearly 73 pounds per cubic foot.

TABLE XVI

WEIGHTS AND SPECIFIC GRAVITY OF WATER

	Weight per Cubic Foot, 62° F.	Specific Gravity.
Pure water	62.355	1.00000
Atlantic Ocean	64.043	1.0275
Lake Michigan	62.336	1.0011
Great Salt Lake, Utah	72.925	1.17
Mono Lake, Cal	65.134	1.045
Mississippi River	62.333	1.00006
Delaware River	62.333	1.00006

All natural waters always contain in solution more or less of the substances with which they have come in contact in their courses, although these substances may be invisible. These impurities may be either solids, liquids or gases. The quantity of a solid that can be dissolved by a liquid is fixed and limited, and is always the same for the

same temperature, the solubility generally increasing with the temperature. The same quantity of gas will also be dissolved by a liquid if the temperature and the pressure remain the same, the volume of gas dissolved being proportional to the atmospheric pressure. Rain water always contains in solution a certain amount of the natural gases of the atmosphere. These are, however, not dissolved in proportion to their occurrence in the atmosphere, but more nearly in proportion to the solubility of the gases. Deep waters and waters of springs which have been under pressure carry in solution larger percentages of carbonic acid gas than natural waters.

There is a distinct difference between solution and suspension. When in suspension, a substance still retains its physical identity, although it may be held in a very finely divided state and thus be carried in suspension for indefinite periods. When the water is at rest the heavier suspended particles are soon deposited.

Volume. For all practical purposes, water may be considered non-compressible. The coefficient of compressibility ranges from 0.00004 to 0.00005 per atmosphere at ordinary temperature, the coefficient decreasing as the temperature increases.

Table XVII gives the relative volume and weight of pure water at various temperatures, as compared with its volume at 39.2° F.

Critical Temperatures. There are four temperatures of water which are often used in physical calculations and which should be kept in mind: viz., 32° F., or 0° C.; 39.2° F., or 4° C.; 62° F., or 16.67° C.; and 212° F., or 100° C.

At 32° F., or 0° C., pure water freezes at one atmosphere pressure (sea level). The weight of ice is 57.5 pounds per cubic foot; when floating in pure water 92 per cent of its mass is submerged, while in sea water about 89 per cent is submerged.

39.2° F. or 4° C., is the approximate point of maximum density of pure water.

62° F. or 16.67° C., is the British Standard temperature, and is used as a basis in calculating the specific gravity of bodies, in England and the United States.

212° F. or 100° C. is the boiling point of pure water at atmospheric pressure.

Latent Heat. This is the heat that apparently disappears during some change in the conditions of a body, without increasing its temperature. To transform ice, water and vapor, or steam, from one state to the other, it is only necessary to supply a certain quantity of heat energy, −460° F. being the absolute zero of temperature.

Thus, in melting 1 pound of ice into water at 32° F., about 142

heat-units are absorbed and become latent; while in freezing one pound of water into ice, a like quantity of heat is given out to the surrounding medium.

TABLE XVII

VOLUME AND WEIGHT OF PURE WATER AT VARIOUS TEMPERATURES
(From Marks and Davis)

Temperature in Degrees Fahrenheit.	Relative Volume.	Weight per Cubic Foot in Pounds.	Temperature in Degrees Fahrenheit.	Relative Volume.	Weight per Cubic Foot in Pounds.
32	1.000176	62.42	130	1.01420	61.55
39.2	1.000000	62.43	140	1.01705	61.38
40	1.000004	62.43	150	1.02011	61.20
50	1.00027	62.42	160	1.02337	61.00
60	1.00096	62.37	170	1.02682	60.80
70	1.00201	62.30	180	1.03047	60.58
80	1.00338	62.22	190	1.03431	60.36
90	1.00504	62.11	200	1.03835	60.12
100	1.00698	62.00	210	1.04256	59.88
110	1.00915	61.86	212	1.04343	59.83
120	1.01157	61.71			

Latent heat is not lost, but reappears whenever the substances pass through a reverse cycle, from a gaseous to a liquid, or from a liquid to a solid state. It may, therefore, be considered as the heat which apparently disappears, or is lost to the thermometric measurement, when the molecular constitution of a body is being changed.

Specific Heat. The specific heat of water is greater than that of any other known substance, with the exception of bromine and hydrogen, and it is the basis for measurement of the capacity of heat absorption of all other substances. Its value varies with the temperature of the water, being lowest near 40° C., after which it increases up to and beyond the boiling-point. The generally accepted values, as determined by Peabody, are given in Table XVIII.

Effect of Atmospheric Pressure. At sea level the average atmospheric pressure is 14.72 pounds per square inch, but it decreases as the height above sea level increases. With water weighing 62.4 pounds per cubic foot, the weight of a column having a cross-section of 1 square inch and a height of 1 foot will equal $\frac{62.4}{144}$ or 0.43 pound, so that at sea level water will rise to an average height of $\frac{14.72}{0.43}$ or 33.9 feet in vacuum.

The barometric pressure in inches is equal to the pressure per square inch divided by 0.4908.

TABLE XVIII

SPECIFIC HEAT OF WATER AT VARIOUS TEMPERATURES

Temperature.		Specific Heat.	Temperature.		Specific Heat.
Degrees Centigrade.	Degrees Fahrenheit.		Degrees Centigrade.	Degrees Fahrenheit.	
0	32	1.0094	50	122	0.9980
5	41	1.0053	55	131	0.9985
10	50	1.0023	60	140	0.9994
15	59	1.0003	65	149	1.0004
16.11	61	1.000	70	158	1.0015
20	68	0.9990	75	167	1.0028
25	77	0.9981	80	176	1.0042
30	86	0.9976	85	185	1.0056
35	95	0.9974	90	194	1.0071
40	104	0.9974	95	203	1.0086
45	113	0.9976	100	212	1.0101

In Table XIX are given the relations of altitude to barometer and atmospheric pressure.

Measurements. Conversion Table XX gives the most common units in which water is measured.

2. RAINFALL

Source of Water Supply. The ultimate source of our water supply is the precipitation in the form of rain or snow which reaches the earth. For the United States, the chief source of this is the evaporation from the Pacific Ocean, carried eastward in diminishing quantities by westerly winds. In the Mississippi Valley, the small supply of moisture still remaining is augmented by a generous contribution from the Gulf of Mexico, whence it is carried inland by southerly and southwesterly winds. East of the Appalachian Mountains, the precipitation is mainly derived from the Atlantic Ocean.

Rain is formed whenever the air is cooled below the point of saturation. This cooling may be caused by the air currents being forced upward, as when they strike mountain ranges; or they may be intermingled with other colder air currents, or come into contact with a cold land.

TABLE XIX

Relations of Elevation to Barometer and Atmospheric Pressure

Height above Sea Level.	Average Height Barometer in Inches of Mercury.	Average Pressure in Pounds per Square Inch.	Average Height to which Water Will Rise in an Exhausted Tube.
0	30.00	14.72	33.96
100	29.89	14.67	33.84
200	29.78	14.62	33.72
300	29.68	14.57	33.60
400	29.57	14.51	33.48
500	29.47	14.46	33.35
600	29.36	14.41	33.23
700	29.25	14.36	33.11
800	29.15	14.30	32.99
900	29.04	14.25	32.87
1,000	28.94	14.20	32.76
1,250	28.67	14.07	32.47
1,500	28.42	13.95	32.19
2,000	27.92	13.70	31.61
2,500	27.40	13.45	31.04
3,000	26.93	13.21	30.49
3,500	26.43	12.98	29.94
4,000	25.98	12.74	29.41
4,500	25.51	12.51	28.89
5,000	25.06	12.29	28.37
6,000	24.18	11.85	27.37
7,000	23.32	11.43	26.40
8,000	22.50	11.04	25.47
9,000	21.70	10.65	24.57
10,000	20.93	10.28	23.70

TABLE XX

Equivalent Measures and Weights of Water at 4° Centigrade, 39.2° Fahrenheit

U. S. Gallons.	Liters.	Cubic Meters.	Pounds.	Cubic Feet.	Cubic Inches.
1.	3.7853	.0037853	8.34112	.13368	231.
1.20017	4.54303	.004543	10.0108	.160439	277.274
.264179	1.	.001	2.20355	.035316	61.0254
264.179	1000.	1.	2203.55	35.31563	61025.4
.119888	.453813	.0004538	1.	.0160266	27.694
7.48055	28.3161	.0283161	62.3961	1.	1728.
.004329	.0163866	.0000164	.0361089	.0005787	1.
.0408	.1544306	.0001544	.340008	.005454	9.4224

Variation in Rainfall. The rainfall varies greatly in different parts of the country and is governed quite largely by the geographic or topographic relations. It is usually given in either total inches of rain per year or per month, while the daily maps of the Weather Bureau show the variations from day to day. A map of the United States, giving the average annual rainfall in inches for the different sections, is shown in Fig. 13, the mean annual precipitation for the whole country being 29.4 inches. Table XXI also gives some typical values of rainfall in different parts of the country.

TABLE XXI

TYPICAL AVERAGES OF RAINFALL

	Inches Annual Rainfall.	Approximate Mean Annual Run-off, Inches.
North Atlantic States	40–50	Over 20
Gulf States	50–60	Over 20
Lake Region	30–40	10–20
Mississippi Valley	30–60	10–20
Mountain Region	10–20	2– 5
Plains	0–10	0– 2
Pacific Coast, north	40–60	10—Over 20
Pacific Coast, south	10–30	2–10

State.	Spring.	Summer.	Autumn.	Winter.	Total.
Massachusetts	11.6	11.4	11.9	11.7	46.6
Georgia	12.4	15.6	10.7	12.7	51.4
Michigan	7.9	9.7	9.2	7.0	33.8
Missouri	10.0	12 0	9.1	6.5	38.0
Colorado	4.2	5.5	2.8	2.3	14.8
Nevada	2.3	0.8	1.3	3.2	7.6
Oregon	9.8	2.7	10.5	21.0	44.0
California	6.2	0.3	3.5	11.9	21.9

The annual, as well as the monthly, rainfall varies irregularly from year to year, and the amount of these variations is greater in some localities than in others. While they may remain within certain limits, the totals are made up of still greater variations in individual storms.

The rainfalls to be considered for practical purposes are the average monthly and the monthly of the driest year, both of which affect the supply. A knowledge of the maximum rainfall is essential for determining the discharge.

Rainfall Record. The United States Weather Bureau maintains several thousand stations for recording the rainfall of the country, and

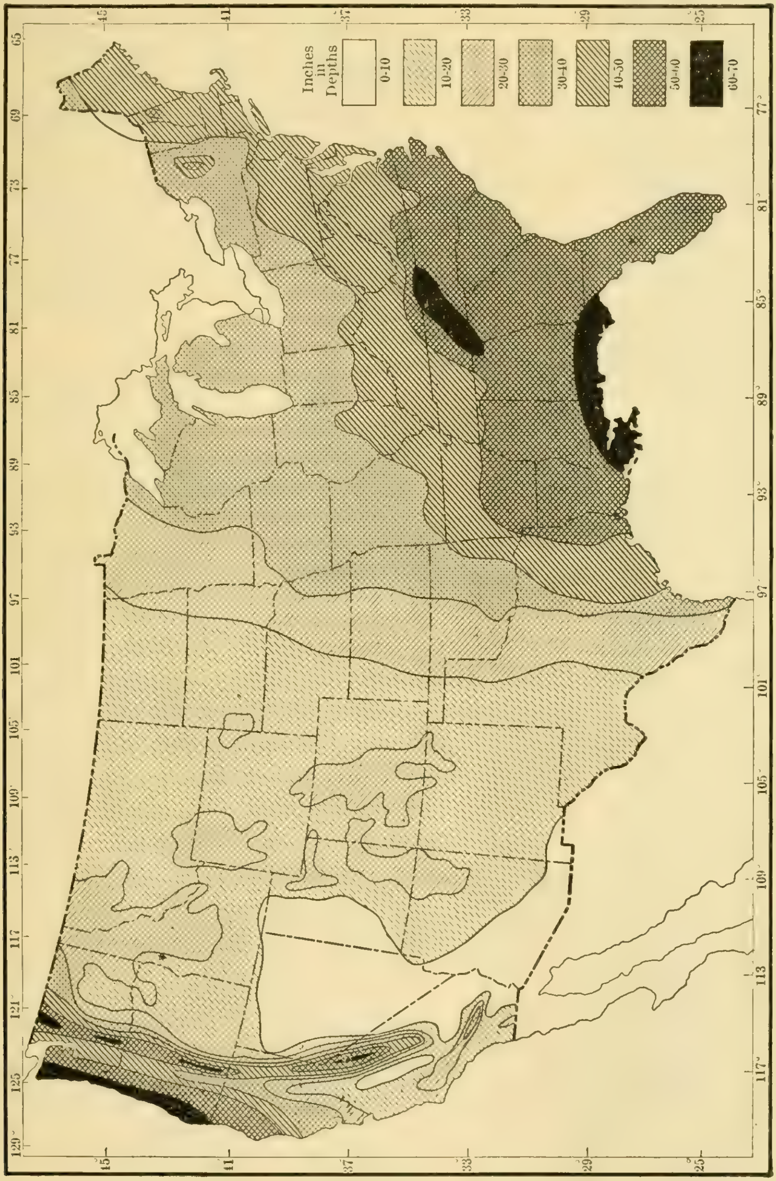


FIG. 13.—Map of United States Showing Mean Annual Precipitation.

the number of points at which such observations are made is increasing from year to year. There are some places where observations have

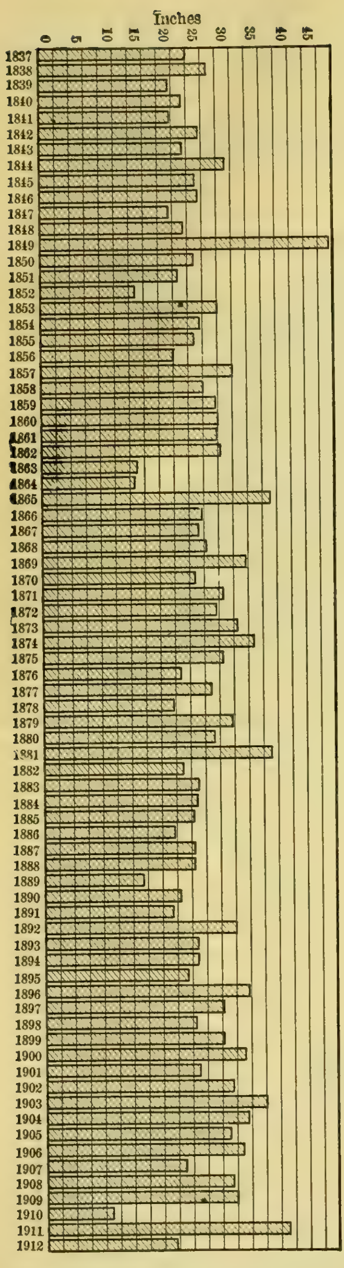


FIG. 14.—Annual Precipitation at St. Paul, Minn., 1837–1912.

been taken for over fifty years, and sufficient information can therefore usually be obtained from the bulletins of the Weather Bureau. Where small watersheds are under investigation, it may, however, often be found necessary to make individual rainfall measurements.

Figures 14 and 15 are diagrams representing a seventy-five-year rainfall record at St. Paul, as reported by the Minnesota Board of Water Commissioners.

3. DISPOSAL OF RAINFALL

A portion of the rainfall evaporates, a portion enters the soil and is either absorbed by plant growth or, by ground flow, reaches the rivers or lakes; while the third portion finds its way into streams as surface flow or run-off.

Evaporation. Of the tremendous losses due to evaporation from the ground surface comparatively little is known. It is impossible to arrive at such losses by taking the difference between rainfall and run-off, as in this there would also be included the losses due to absorption by the soil and by vegetation. Again, the rate of run-off does not altogether depend upon the rainfall.

The rate of evaporation, or the proportion of the rainfall to the air, varies greatly under different conditions and is affected by atmospheric conditions as well as by the character of the soil. The capacity of the atmosphere to take up and dissipate the moisture depends in turn on the temperature, the wind, and the degree of saturation of the wind.

Wind increases the evaporation to a great extent, especially from exposed water surfaces, as the saturated air in contact with such surfaces is rapidly removed and continually replaced by fresh air. In cool climates with light breezes, the evaporation is considerably lower than in warm climates with strong winds.

The nature of the earth's surface, on the other hand, determines the rate at which moisture is supplied. Thus a very large evaporation takes place from exposed water surfaces such as lakes, swamp lands, etc., and the amount may, in certain instances, equal the actual rainfall itself. Such surfaces tend, however, as a storage of flood waters and thus assist materially in the regulation of the stream flow.

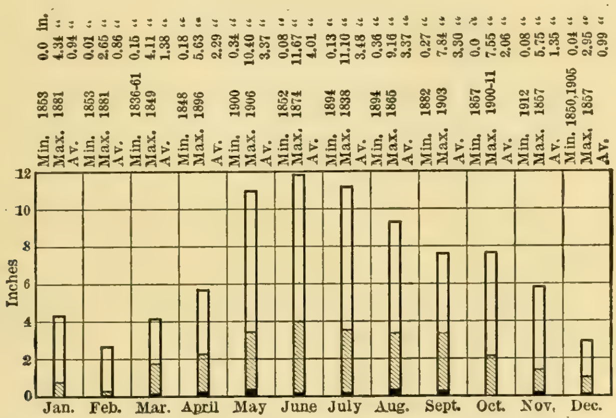


Fig. 15.—Monthly Variation in Precipitation at St. Paul, Minn. From Records 1837–1912.

The depth to the water in the soil, and its capillary action in bringing the water to the surface, also naturally affect the evaporation. A light rain falling on an impervious rock surface may simply wet the surface and quickly disappear as vapor, while saturated surface layers of the soil, such as exist after heavy rains, will also cause considerable evaporation.

A large amount of water is necessarily taken up by the vegetation and evaporated, while forests cause much less evaporation than open fields.

A more complete study has been made of the evaporation from the water surface of lakes and rivers, the greatest use of such studies being in the investigation of storage and the losses which are likely to occur on such reservoirs through evaporation. That the losses on lake

areas are very great, and often of greater extent than precipitation, is well known.

The map in Fig. 16 shows the mean average evaporation, in the United States, from open waters. It was compiled from observations of the United States Weather Bureau in 1887 and 1888.[1]

Absorption. A considerable part of the rain which falls on the earth is absorbed by the ground. The amount varies greatly, however, depending on the rate of precipitation, texture of soil, slope of drainage surface, temperature and vegetation.

A light shower will usually be quickly evaporated, while a heavier rain may be absorbed, and if the heavy rain lasts for some time there will be an excess amount of water which will run off to the nearby stream. On the other hand, less may be absorbed during a heavy rain than during a light, gentle rain, because each type of soil has a certain rate of absorption due to its porosity, and if the water is supplied more rapidly than it can be taken up, the excess runs off. A deep, porous, sandy soil naturally will absorb and hold more water than a compact, shallow one, such as a clayey soil.

If the slope of the watershed is very steep, the water may drain off before any can be absorbed by the soil; and if the slopes are rocky, practically no water is absorbed.

Temperature also necessarily affects absorption. A high temperature increases it, while the opposite effect is produced by a low temperatures, as when the ground is frozen.

On slopes, vegetation and forest are of the greatest importance in that they retard part of the drainage water during heavy rains, giving the soil time to absorb the same. They are, therefore, of great value in reducing the intensity of floods after severe storms. The absorbed water seeps into the ground, which it saturates, and some of it percolates still further into the pores and fissures and trickles slowly toward the stream.

These ground waters have a most important bearing on the stream flow. Areas of little or no underground flow are subject to violent floods and extreme droughts, while areas with a large proportion of underground storage are comparatively free from floods. The greater part of the low-water of streams having no lakes or swamps in their watershed is also supplied by this underground flow.

A determination of the exact quantity of underground waters is a very difficult problem. Numerous papers have been prepared on the subject by different authors. Water Supply and Irrigation Paper No. 163 of the United States Geological Survey contains a bibliographic

[1] Monthly Weather Review, September, 1888.

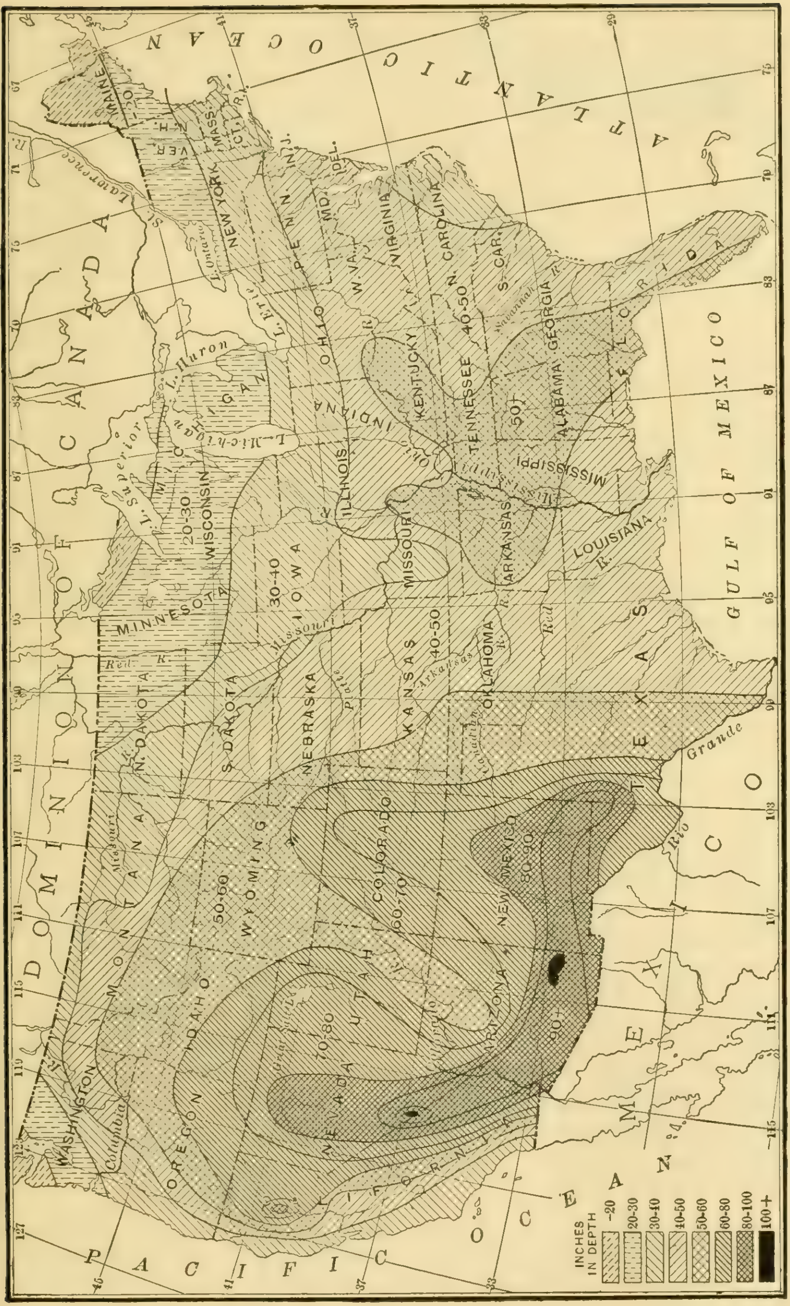


FIG. 16.—Map Showing Mean Annual Evaporation in United States.

review and index of underground-water literature published in the United States up to and including the year 1905.

Run-off. The run-off is that part of the rainfall which drains off the surface of the watershed in visible streams. It is that part of the rainfall which remains after nature's need of moisture has been supplied in the form of evaporation and absorption.

The close relation between these three subdivisions of rainfall has been referred to in the above, and it follows that the run-off is affected, both directly and indirectly, by the same factors that govern the rate of evaporation and absorption.

It is often important to know the relation between rainfall and run-off, as this may in many instances be the only way to ascertain the flow of a stream. Rainfall observations have been made for many years, and it may be possible, by knowing the ratio between run-off and rainfall for a certain drainage area, to apply this value to a watershed in another place. It is, of course, of the greatest importance, in such comparisons, that the areas compared be of similar character. They must also be of approximately the same size, because smaller drainage areas usually have a wider variation between maximum and minimum run-off than large ones.

It is apparent that there can be no constant relation between the rainfall and the run-off for the whole country, although in this respect the ratio for the Eastern States is much more constant than for the Western States. There are also great variations in the yearly, as well as the monthly and daily, run-off, and it is very difficult to make accurate estimates as to what the two latter may be expected to be; the daily run-off is, of course, almost impossible to foretell. The yearly run-off, however, bears a more nearly uniform ratio to the rainfall, so that with a good knowledge of the presence of forests, character of soil, climate, etc., a fairly accurate estimate of the yearly run-off may be made, based on known values under similar conditions.

As for rainfall, run-off is also usually expressed in inches, and the map in Fig. 17 shows approximately the mean annual run-off for the country. By comparing this map with that of rainfall in Fig. 11, a fairly good idea of the relation between rainfall and run-off may be had. Table XXII furthermore gives the run-off for various watersheds in the United States.

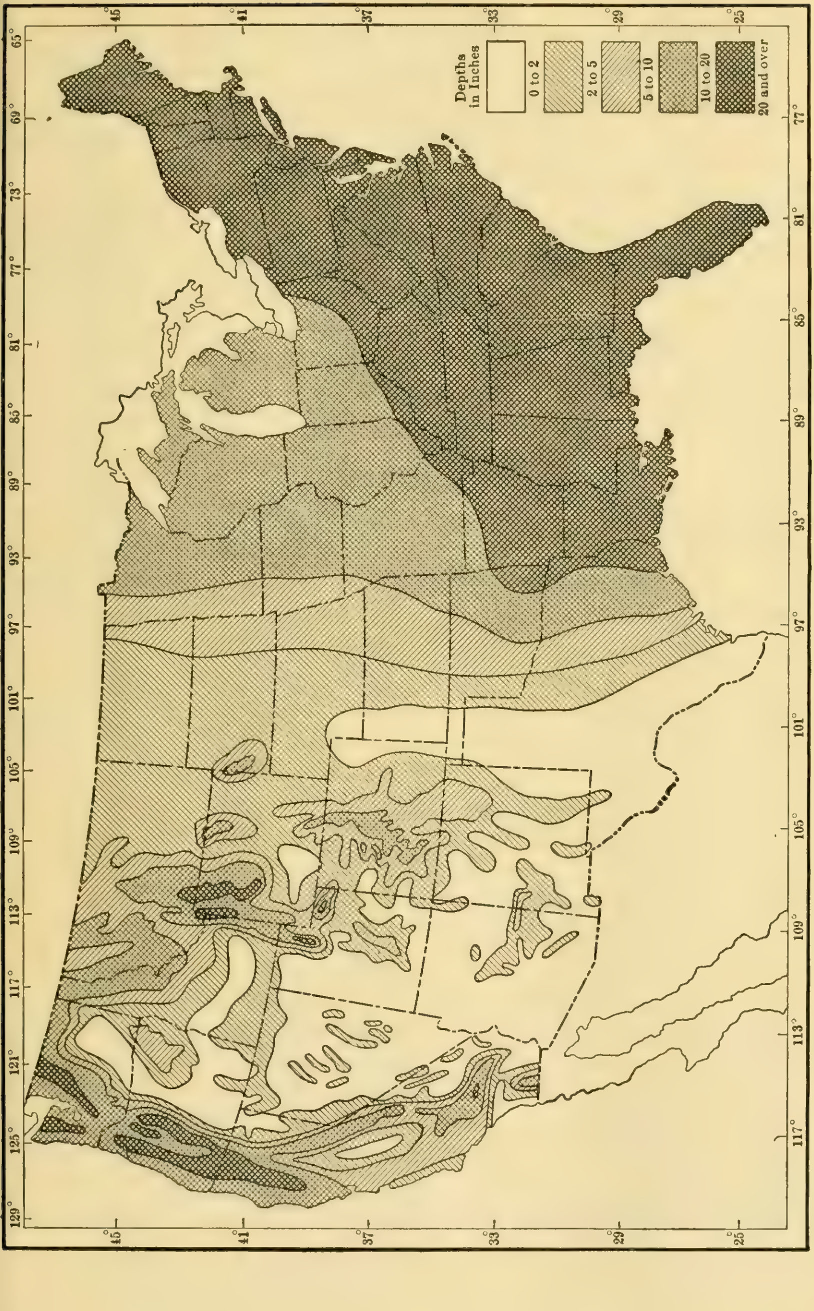


FIG. 17.—Map of Mean Annual Run-off throughout United States.

TABLE XXII

MEAN ANNUAL RUN-OFF FOR VARIOUS WATERSHEDS IN UNITED STATES [1]

River.	Point of Measurement.	Drainage Area Square Miles.	Period.	Run-off in Depth in Inches on Drainage Area.
Kern	Bakersfield, Cal	2,340	1896–1905	4.36
San Joaquin	Herndon, Cal	1,640	1896–1901	20.47
Kings	Sanger, Cal	1,740	1897–1906	20.38
Sacramento	Red Bluff, Cal	4,300	1902–1906	24.06
Umatilla	Umatilla, Ore	2,130	Nov. 1, 1900. to Dec. 31. 1900	3.94
Willamette	Albany, Ore	4,860	Jan. 1, 1899, to Dec. 31, 1908	46.62
Boise	Boise, Idaho	2,610	1895–1904	15.60
Green	Green River, Wyo	7,450	May 1, 1896, to Oct. 31, 1906	4.81
Laramie	Uva, Wyo	3,180	May, 1895, to Oct., 1903	1.10
Red	Grand Forks, N. Dak.	25,100	Sept., 1902, to Sept., 1908	2.08
Rio Grande	Rio Grande, N. Mex.	14,000	Jan. 1, 1896, to Dec. 31, 1905	1.46
Animas	Durango, Cal.	812	July, 1895, to Dec., 1905	14.86
South Platte	Denver, Col	3,840	Jan. 1, 1896, to Nov. 30, 1906	1.44
Green	Greenriver, Utah	38,200	Jan., 1895, to Dec., 1908	3.17
Logan	Logan, Utah	218	1896–1900 1904–1906	21.18
Carson	Empire, Nev	988	Nov., 1900, to Dec., 1906	6.25
Truckee	Vista, Nev	1,520	Sept., 1899, to Dec., 1906	9.18
Humboldt	Orleans, Nev	13,800	Jan., 1897, to Dec., 1906	0.25
Colorado	Yuma, Ariz	225,000	Jan., 1902, to Dec., 1906	1.15
St. Croix	St. Croix Falls Wis.	6,370	1902–1904	10.60
Menominee	Iron Mountain, Mich.	2,420	Sept., 1902, to Sept., 1906	18.92
Illinois	Peoria, Ill	13,200	Apr. 1, 1903, to Jan. 30. 1906	14.11
Maumee	Waterville, Ohio	6,110	Dec., 1898, zo Jan., 1902	13.61
Scioto	Columbus, Ohio	1,050	1899 to July, 1906	10.43
Duck	Columbia, Tenn	1,260	Nov. 1, 1904, to Dec. 31, 1908	18.87
Tennessee	Chattanooga, Tenn	21,400	1899–1908	23.63
Tombigbee	Columbus, Miss	4,440	1905–1908	15.48
Black Warrior	Cordova, Ala	1,900	1900–1908	19.37
Alabama	Selma, Ala	15,400	1900–1908	24.01
Savannah	Augusta, Ga	7,300	1899–1908	22.29
Catawba	Rock Hill, S. C.	2,990	1895–1903	25.21
Tar	Tarboro, N. C.	2,290	1896–1900	13.89
Roanoke	Randolph, Va	3,080	1901–1905	18.86
Potomac	Pt. of Rocks, Va.	9,650	1895–1906	14.40
Oswego	Oswego, N. Y	5,000	1897–1901	11.69
Delaware	Port Jarvis, N. Y	3,250	1904–1908	22.20
Susquehanna	Binghamton, N. Y	2,400	1901–1906	28.88
Hudson	Mechanicsville, N. Y.	4,500	1891–1900	22.95
Mohawk	Dunsbach Ferry, N. Y.	3,440	1898–1907	23.28

[1] Prepared by Newell and Murphy from U. S. Geological Survey Records.

4. STREAM-FLOW

Definition of Terms. The volume of water flowing in a river is generally defined as " stream-flow " and is expressed in various terms, depending upon the particular class of work for which it is to be used. The term used in the reports of the United States Geological Survey are second-feet, second-feet per square mile, acre-feet, and depth in inches. Of these, the first two represent the rate of flow only, while the two latter represent the actual quantity of water. They are defined in the Survey Reports as follows:

" Second-foot " is an abbreviation for cubic foot per second and is the unit for the rate of discharge of water flowing in a stream 1 foot wide, 1 foot deep, at a rate of 1 foot a second. It is generally used as a fundamental unit from which others are computed by the use of the factors given in the following table of equivalents.

" Second-feet per square mile " is the average number of cubic feet of water flowing per second from each square mile of area drained, on the assumption that the run-off is distributed uniformly both as regards time and area.

" Depth in inches " is the depth to which the drainage area would be covered if all the water flowing from it in a given period were conserved and uniformly distributed on the surface. It is used for comparing run-off with rainfall, which is usually expressed in depth in inches.

An " acre-foot " is equivalent to 43,560 cubic feet, and is the quantity required to cover an acre to the depth of 1 foot. The term is commonly used in connection with storage for irrigation.

The direct cause of stream-flow is the visible run-off from the watershed and that part of the rain-fall which was absorbed by the soil and which slowly finds its way to the stream bed in the form of an underground flow.

Variation in Stream-Flow. There is a very considerable variation in the flow of rivers, not only during the various months of the year, but from year to year as well; and the variation is greater in some regions than in others. In Fig. 18 are shown some typical hydrograph records of New York streams, which clearly illustrate what may be expected in the way of variations in stream-flows. While they are of entirely different characteristics, it can be seen that there are certain common features in that the flows are heaviest during the spring and early summer and lowest in autumn.

This irregularity of flow is a very important factor in any water-power development and one that necessitates reckoning with the mini-

mum flow and the possibilities of storage for increasing the same, in order to develop the enterprise safely.

Factors Affecting Stream Flow. It was previously shown how absorption and the natural storage of underground waters had a very

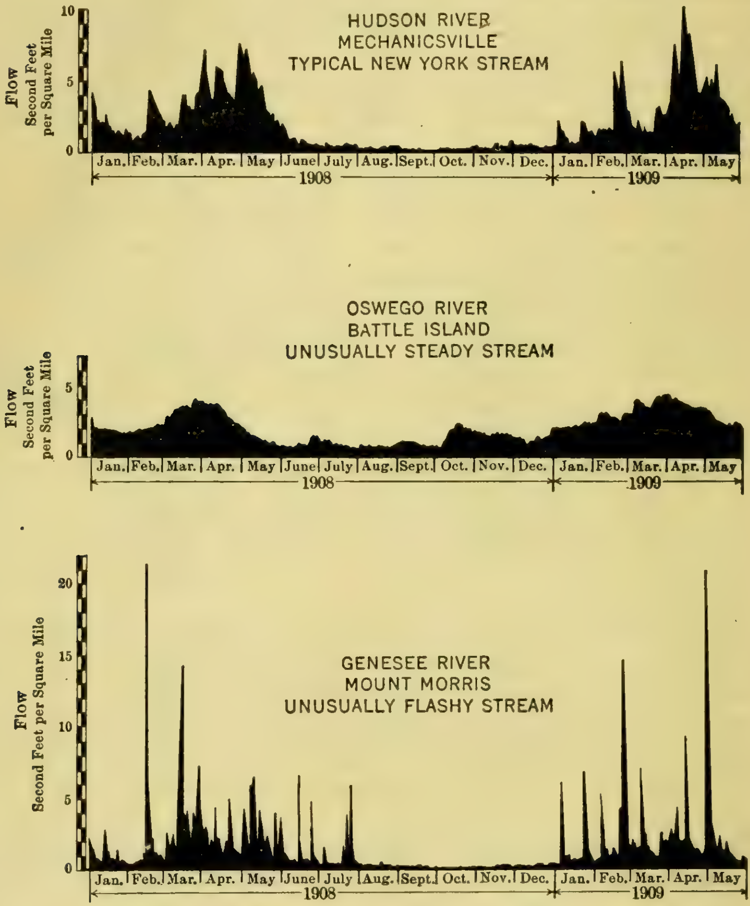


FIG. 18.—Hydrographs Showing Natural Fluctuations of Flow of New York State Streams.

important bearing on the regularity of the stream-flow, these waters being the main source of supply during the dry season. It was also shown how vegetation and heavy forests will interpose an appreciable time element in the run-off. In addition, there are several other factors which may delay the same. For example, where snow and ice form to considerable depths, a large part of the precipitation may be

stored for weeks or months. On the other hand, the effect of an abnormally dry or wet season may extend beyond a single year, since it somewhat affects the conditions of the ground during the next year. In this way, a succession of dry or wet years may disturb the expected relations of run-off to rainfall, producing unexpected drought or flood.

Most watersheds have some natural storage features tending to equalize the stream-flow as compared with the rainfall. In the northern part of the United States, most watersheds have distinct periods in the water year as distinguished from the calendar year. These are usually classified as storing, growing, and replenishing periods. Beginning about the first of December, water begins to accumulate in the form of snow or ice, or in the soil, and for months there is an increasing storage. With the beginning of spring, the storage period terminates, and the growing period begins, during which moisture is absorbed. By harvest time vegetation has ceased to absorb moisture and it usually tends to replenish the ground until the end of the fall. That these periods have great effects on run-off can readily be appreciated, and how great the effects may be can well be judged from the typical figures in Table XXIII.

TABLE XXIII

Hudson River, 1888–1901

Catchment Area, 4500 Square Miles

Mean Values

Period.	Rainfall in Inches.	Run-off in Inches.	Evaporation in Inches.	Per Cent Run-off to Rainfall.
Storage	20.6	16.1	4.5	78.2
Growing	12.7	3.5	9.2	27.6
Replenishing	10.9	3.7	7.2	34.0
	44.2	23.3	20.9	52.7

The curves in Fig. 19 indicate graphically the approximate relations for this area, and will show that for the same watershed the percentage run-off increases with increasing rainfall.

Lakes, ponds and swamps are, of course, of great value in regulating the stream-flow, and broad rivers very frequently have storage possibilities not readily appreciated at first. In localities where there is a pronounced dry season extending over several months' time, water-power plants have been built in which it is regularly proposed to store

water for six months at a time, thus making it possible to increase the average daily output of the plant several fold. This occurs usually in high-head plants where the quantity of water is relatively small and the rough character of the country permits the construction of deep reservoirs, but there are some low-head plants with short periods of low water where the storage of some important tributary stream will, at reasonable expense, greatly increase the minimum average daily output.

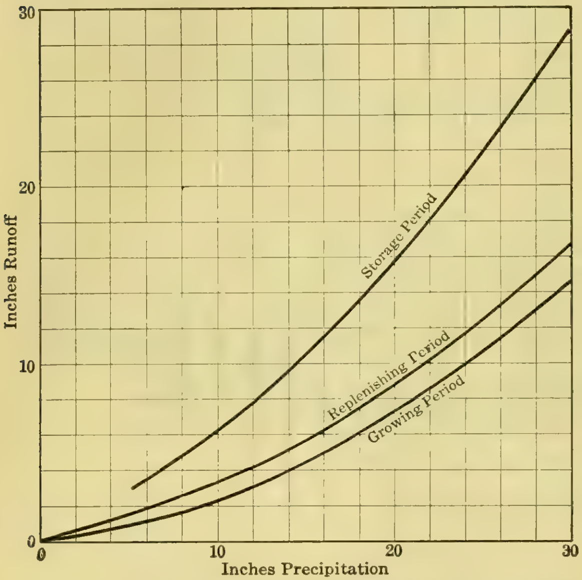


FIG. 19.—Curves Showing Mean Rainfall and Run-off on Upper Hudson River.

The diagrams [1] shown in Fig. 20 represent the ideal regulation of the Hudson River, and were based on a proposed extensive reservoir system and the stream-flows for the years 1908–09. Other stream-flow records would, of course, modify the result, while, on the other hand, such ideal flow can seldom be obtained at a cost which would be commercially possible.

From the above it can readily be seen that very careful measurements of stream-flow, extending over many years' time, are usually necessary to enable good estimates of available power to be made, particularly where the contemplated development has no storage facilities.

Measurements of Stream-flow. The methods by which the records of stream discharge are made differ according to the nature and importance of the work. The simplest and most accurate method for a small stream is by means of a weir. This consists of a dam extending across and at right angles to the stream, and having a rectangular notch cut in the top plank, with both side edges and bottom sharply beveled toward the intake, as shown in Fig. 21. The bottom of the notch,

[1] D. W. Mead, "Flow of Streams."

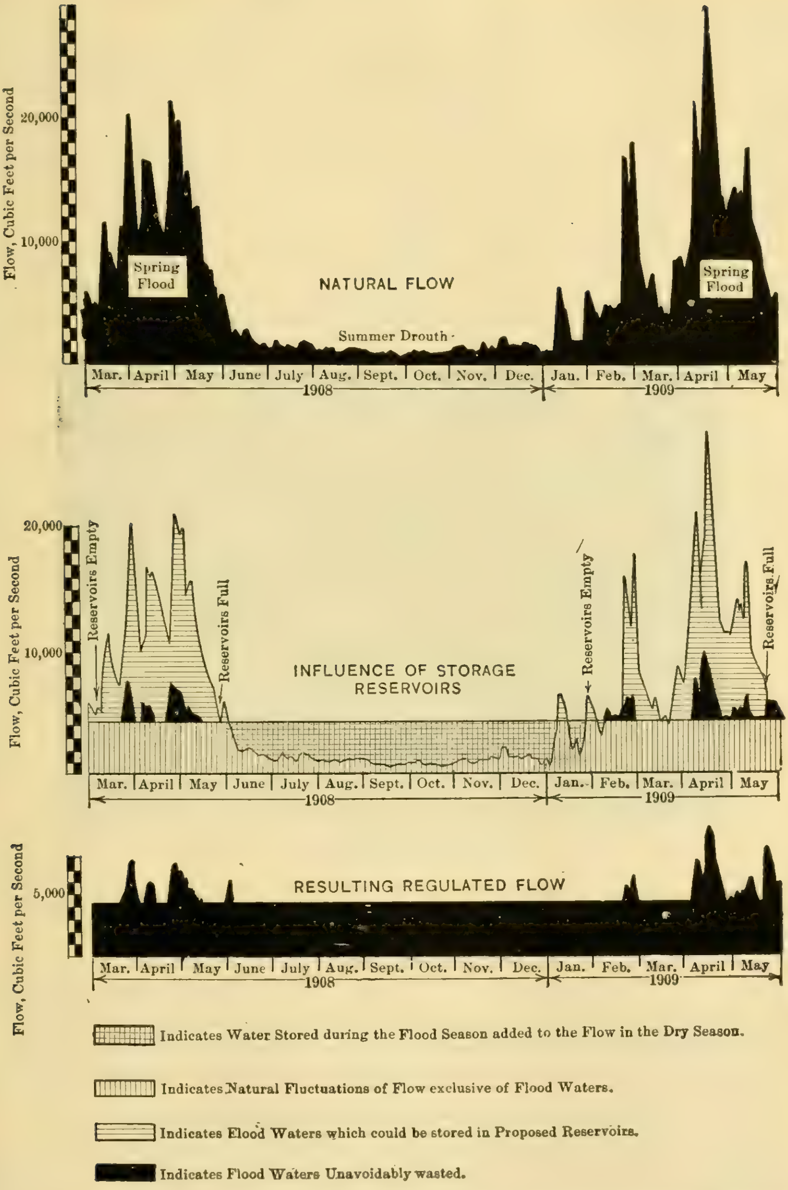


FIG. 20.—Diagrams Illustrating Typical Regulating Effect of Proposed Reservoirs on the Flow of the Hudson River.

which is called the "crest" of the weir, should be perfectly level and the sides vertical.

There are certain proportions which must be observed in the dimensions of this notch. Its length, or width, should be between four and eight times the depth of water flowing over the crest of the weir. The pond back of the weir should be at least 50 per cent wider than the notch, and of such width and depth that the velocity of flow or approach be not over 1 foot per second.

On the up-stream side, a stake is driven down in the bottom of the pond, near the bank, so that its top is level with the bottom edge of the notch, this level being easily found when the water is beginning to

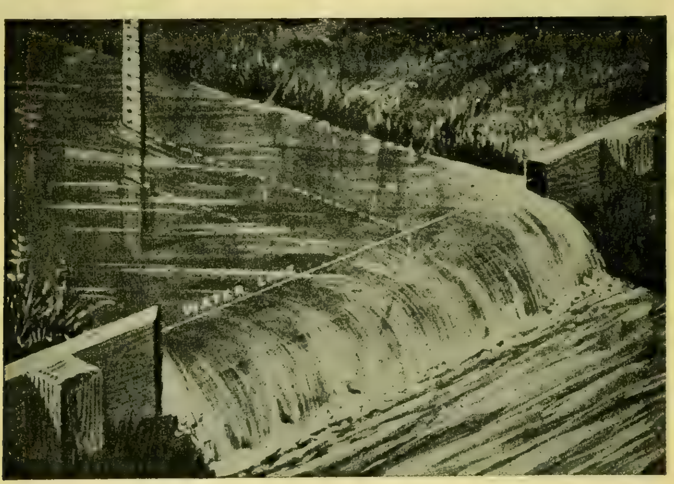


FIG. 21.—Weir for Measuring Flow of Water.

spill over the crest. The stake should be placed several feet from the board, at least as far from it as the length of the notch.

By means of a rule, as shown in the illustration, the depth of water over the top of the submerged stake is measured, allowance being made for the capillary attraction of the water against the sides of the weir. When this depth has been ascertained, the amount of water flowing over the weir may be readily found from Table XXIV.

For example: Suppose the weir to be 72 inches long, and the depth of water over the stake to be $11\frac{5}{8}$ inches. Follow down the left-hand column of the figures in the table until you come to 11 inches. Then run across the table on a line with the 11, until under $\frac{5}{8}$ on top line, you will find 15.85. This multiplied by 72, the length of weir, gives 1141.2, the number of cubic feet of water passing per minute.

TABLE XXIV

Table for Weir Measurement

Giving cubic feet of water per minute, that will flow over a weir 1 inch long and from $\frac{1}{8}$ to $20\frac{7}{8}$ inches deep.

Depth, Inches.		$\frac{1}{8}$	$\frac{1}{4}$	$\frac{3}{8}$	$\frac{1}{2}$	$\frac{5}{8}$	$\frac{3}{4}$	$\frac{7}{8}$
0	.00	.01	.05	.09	.14	.19	.26	.32
1	.40	.47	.55	.64	.73	.82	.92	1.02
2	1.13	1.23	1.35	1.46	1.58	1.70	1.82	1.95
3	2.07	2.21	2.34	2.48	2.61	2.76	2.90	3.05
4	3.20	3.35	3.50	3.66	3.81	3.97	4.14	4.30
5	4.47	4.64	4.81	4.98	5.15	5.33	5.51	5.69
6	5.87	6.06	6.25	6.44	6.62	6.82	7.01	7.21
7	7.40	7.60	7.80	8.01	8.21	8.42	8.63	8.83
8	9.05	9.26	9.47	9.69	9.91	10.13	10.35	10.57
9	10.80	11.02	11.25	11.48	11.71	11.94	12.17	12.41
10	12.64	12.88	13.12	13.36	13.60	13.85	14.09	14.34
11	14.59	14.84	15.09	15.34	15.59	15.85	16.11	16.36
12	16.62	16.88	17.15	17.41	17.67	17.94	18.21	18.47
13	18.74	19.01	19.29	19.56	19.84	20.11	20.39	20.67
14	20.95	21.23	21.51	21.80	22.08	22.37	22.65	22.94
15	23.23	23.52	23.82	24.11	24.40	24.70	25.00	25.30
16	25.60	25.90	26.20	26.50	26.80	27.11	27.42	27.72
17	28.03	28.34	28.65	28.97	29.28	29.59	29.91	30.22
18	30.54	30.86	31.18	31.50	31.82	32.15	32.47	32.80
19	33.12	33.45	33.78	34.11	34.44	34.77	35.10	35.44
20	35.77	36.11	36.45	36.78	37.12	37.46	37.80	38.15

The above table will give results sufficiently close for all practical purposes, but if extreme accuracy is essential the following formula [1] might be used, in connection with measurements obtained from the method previously described:

$$Q = 3.33(L - 0.2H)H^{3/2}.$$

In the above L = length of weir in feet, H = head or depth of flow in feet over weir, as measured on the stake; Q = cubic feet of water per second.

The Gurley Hook Gauge, Fig. 22, is a very useful device for measuring the depth of the water passing over a weir. Its arrangement is such that the readings can be taken by the observer with the greatest possible convenience and at some distance from the surface of the stream being measured.

[1] Pelton Water Wheel Co.

This gauge is used in a box attached to a flume at any convenient point near the weir, the water from the flume being conveyed to the box by rubber or lead pipes, thus indicating the precise level of the water in the flume, the surface of the water in the box being at rest. The exact level of the crest of the weir should be taken by a leveling instrument and rod, and marked by a line drawn in the still water box at the surface of the water. The scale of the gauge being previously set at zero with the vernier, the base is fastened to the box above the water in a vertical position and at such a height that the point of the hook is at the same level as the crest of the weir, the precise point being secured by moving the hook in the tube. The point of the hook will, of course, be under water and level with the crest of the weir.

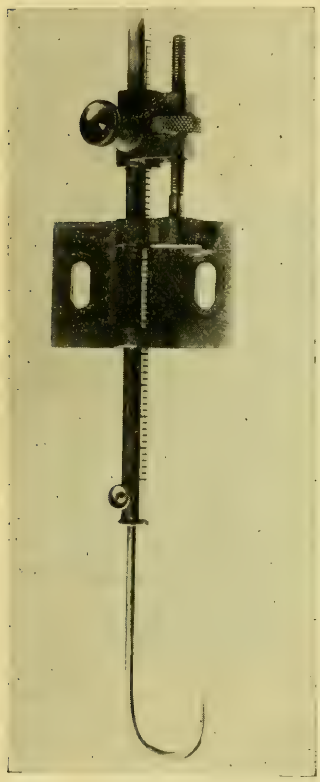


FIG. 22.—Gurley Hook Gauge.

The depth of water flowing over the weir is the distance between the point of the hook in the position named and the exact surface of the water. To ascertain this, the hook is raised by turning the milled head nut until the point of the hook, appearing a little above the surface, causes a distortion in the reflection of the light from the surface of the water. A slight movement of the hook in the opposite direction will cause the distortion to disappear, and will indicate the surface with precision. The reading of the scale will then give the depth of water passing over the weir, in thousandths of a foot.

Where measurement by weir is impracticable, the amount of water can be calculated by ascertaining the average velocity of the water and the cross-section of the stream, the quantity being the product of these two factors. The mean velocity is the function of the cross-section, surface slope, wetted perimeter, and roughness of the bed, while the cross-sectional area depends on the permanency of the bed and the fluctuations of the surface, which govern the depth.

Gauging stations should be located at places where the record of flow is to be made. Bridge locations are preferable, as from them the

measurements can be easily made, with the least expense. If the channel conditions are not satisfactory at such points, it is necessary

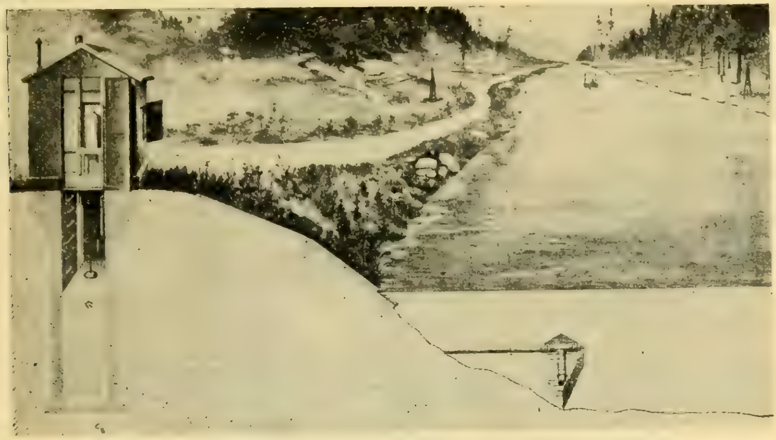


Fig. 23.—Typical Gauging Station with Automatic Gauge.

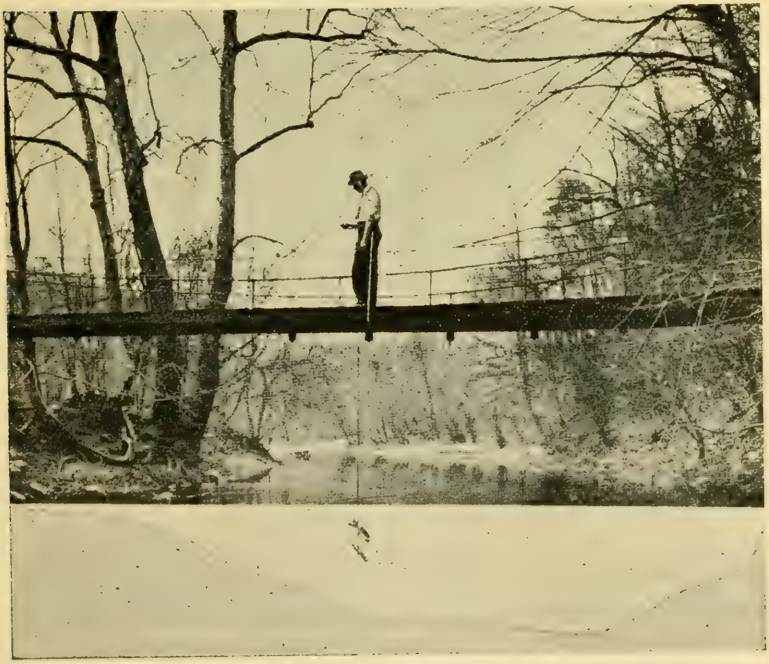


Fig. 24.—Typical Gauging Station for Bridge Measurement.

to use boats or erect a cable station; Fig. 23 shows a typical station used by the United States Geological Survey. It is also preferable

to select a point at which the channel is straight and without cross-currents, both above and below the station, and the bed as free from obstructions as possible.

The methods by which the measurements are made are, in general, those in common use by the United States Geological Survey. An arbitrary number of points are laid off perpendicular to the thread of the stream, Fig. 24. They are known as measuring points and divide

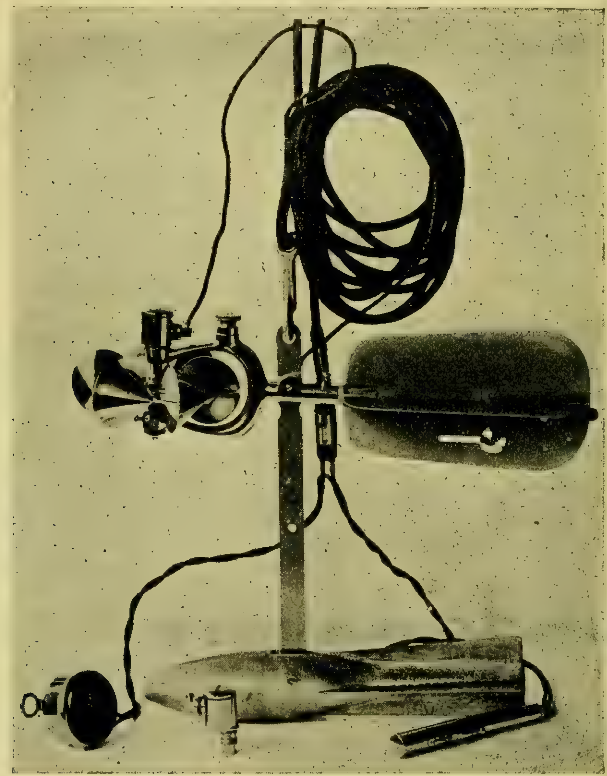


Fig. 25.—Price Electric Current Meter with Telephone Sounder. (Manufactured by W. & L. E. Gurley, Troy, N. Y.)

the gauging section into strips. The area for each strip is calculated from careful soundings and the mean velocity ascertained by making measurements at different depths. By multiplying the area and the velocity for each strip, its discharge value is determined independently of the other, and by adding them together the total is arrived at in the most accurate manner.

The greatest error in these estimates is generally due to inaccurate

determination of the mean daily gauge heights, ordinarily secured from a few observations during the day or even more infrequently. This has led to the introduction of automatic water stage registers (see page 263), by which the varying height of water may be accurately gauged and a dependable, continuous record obtained.

For measuring the velocity, the current meter is now most generally used. This meter is primarily an instrument for measuring the velocity of moving water, and consists essentially of a wheel with vanes, which may be shaped like those of a windmill or of a screw, or with caps like those of an anemometer, the necessary qualification being that

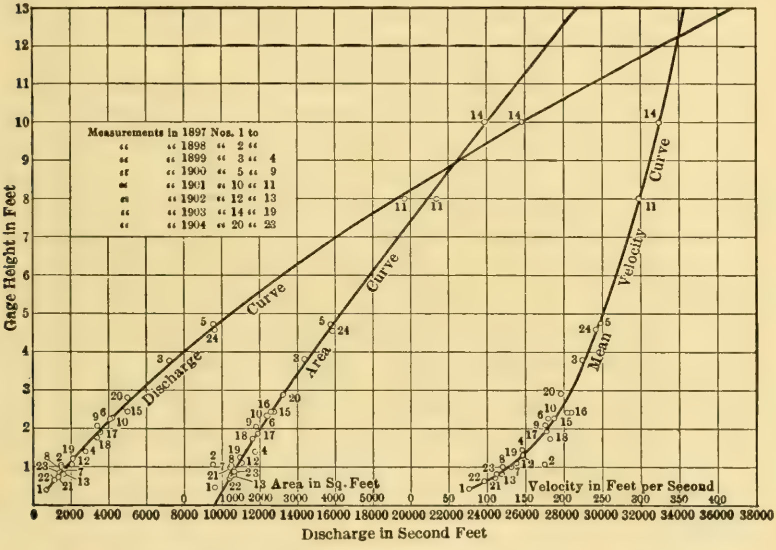


FIG. 26.—Discharge, Mean Velocity, and Area Curves for James River at Cartersville, Va.

the moving water shall easily cause the wheel of the meter to revolve. The velocity of the water is then determined from the revolutions of the meter in unit time. The meter which has been adapted by the United States Geological Survey after years of experience and improvements is the Price Current Meter, which is manufactured by W. & L. E. Gurley. The cable suspended type is shown in Fig. 25, but it is often used on jointed wading rods.

The curves in Fig. 26 show a method of plotting the values of discharge, mean velocity and area in relation to the gauge height.

Where a current meter is not available or its expense not justified, as in minor preliminary investigations, the float method may be used

for approximately determining the velocity. This may be done by laying off 100 feet of the bank and throwing a float into the middle of the stream, noting the time it takes for the same to pass over this 100-foot stretch. This is repeated a number of times and the average taken. As the stream-flow at the surface is greater than at the bottom, the average, which is about 83 per cent of the surface velocity, must be taken. It is, therefore, convenient to lay off the distance as 120 feet and reckon it as 100 feet, using the surface velocity.

Government Records. The Water Supply and Irrigation papers of the United States Geological Survey furnish the chief source of information relating to stream-flow measurements, and a complete list on these may be had by applying to the Director, United States Geological Survey, Washington, D. C.

The United States Weather Bureau also issues annual reports on the flow of the principal rivers of the country, while the War Department from time to time issues reports dealing with special investigations undertaken by the engineers for determining the navigation facilities of certain rivers and the possibilities of their improvement.

In addition to the above Federal Reports, numerous investigations are also made every year by different States. These can, as a rule, be obtained from the Geological Survey Departments of these States.

It is thus seen that there are abundant data on stream-flows in the different sections of the country. These records are, however, scattered around in so many different publications that it is a difficult matter to find the desired information. An excellent system of indexing such data on stream-flow and rainfall has been devised and is used by H. M. Byllesby & Co., Chicago. It is described in *Engineering Record* or January 31, 1914.

5. ENERGY OF FLOWING WATER

The energy of flowing water is entirely due to its position, or head. It follows, in general, the same laws as falling bodies; therefore, assuming a 100 per cent efficiency, its potential energy depending on the position must be equal to its kinetic energy depending on the velocity. That is

$$mgh = \frac{mv^2}{2}$$

where $m = \text{mass} = \frac{w}{g}$;

$g = \text{gravity acceleration} = 32.16$;

$h = \text{head}$;

$v = \text{velocity}$;

$w = \text{weight of water} = 62.4 \text{ lb. per cu. ft.}$

Thus $h=\dfrac{v^2}{2g}$

and $v=\sqrt{2gh}$.

The quantity of flowing water expressed by the formula:

$$q=va;$$

where q = quantity;

v = velocity;

a = area of stream.

From the above, the following formula for calculating the gross horse-power of a stream or body of flowing water may be computed:

$$\text{H.P.}=\frac{Q\times H\times 62.4}{550};$$

in which H.P. = gross horse-power;

Q = discharge of water in cubic feet per sec.;

H = gross head in feet.

The above values are, however, only theoretical and never realized in practice, because of the loss in head due to friction in the water conductors, the nature and value of which will be dealt with in the section on Water Conductors.

6. CONVENIENT EQUIVALENTS

The following is a list of convenient equivalents for use in hydraulic computations:

TABLE XXV

Table for converting discharge in second-feet per square mile into run-off in depth in inches over the area.

Discharge in Second-feet per Square Mile.	Run-off (Depth in Inches).				
	1 Day.	28 Days.	29 Days.	30 Days.	31 Days.
1	0.03719	1.041	1.079	1.116	1.153
2	.07438	2.083	2.157	2.231	2.306
3	.11157	3.124	3.236	3.347	3.459
4	.14876	4.165	4.314	4.463	4.612
5	.18595	5.207	5.393	5.587	5.764
6	.22314	6.248	6.471	6.694	6.917
7	.26033	7.289	7.550	7.810	8.070
8	.29752	8.331	8.628	8.926	9.223
9	.33471	9.372	9.707	10.041	10.376

Note.—For part of month multiply the values for one day by the number of days.

TABLE XXVI

Table for converting discharge in second-feet into run-off in acre-feet.

Discharge in Second-feet.	Run-off in Acre-feet.				
	1 Day.	28 Days.	29 Days.	30 Days.	31 Days.
1	1.983	55.54	57.50	59.50	61.49
2	3.967	111.1	115.0	119.0	123.0
3	5.950	166.6	172.6	178.5	184.5
4	7.934	222.1	230.1	238.0	246.0
5	9.917	277.7	287.6	297.5	307.4
6	11.90	333.2	345.1	357.0	368.9
7	13.88	388.8	402.6	416.5	430.4
8	15.87	444.3	460.2	476.0	491.9
9	17.85	499.8	517.7	535.5	553.4

Note.—For part of month multiply the values for one day by the number of days.

1 second-foot equals 40 California miner's inches (Law March 23, 1901).
1 second-foot equals 38.4 Colorado miner's inches.
1 second-foot equals 40 Arizona miner's inches.
1 second-foot equals 7.48 United States gallons per second; equals 448.8 gallons per minute; equals 646,317 gallons for one day.
1 second-foot for one year covers 1 square mile 1.131 feet or 13.572 inches deep.
1 second-foot for one year equals 31,536,000 cubic feet.
1 second-foot for one day equals 86,400 cubic feet.
1 second-foot equals about 1 acre-inch per hour.
1,000,000,000 (1 United States billion) cubic feet equals 11,570 second-feet for one day.
1,000,000,000 cubic feet equals 414 second-feet for one 28-day month.
1,000,000,000 cubic feet equals 399 second-feet for one 29-day month.
1,000,000,000 cubic feet equals 386 second-feet for one 30-day month.
1,000,000,000 cubic feet equals 373 second-feet for one 31-day month.
100 California miner's inches equals 18.7 United States gallons per second.
100 California miner's inches for one day equals 4.96 acre-feet.
100 Colorado miner's inches equals 2.60 second-feet.
100 Colorado miner's inches equals 19.5 United States gallons per second.
100 Colorado miner's inches for one day equals 5.17 acre-feet.
100 United States gallons per minute equals 0.223 second-foot.
100 United States gallons per minute for one day equals 0.442 acre-foot.
1,000,000 United States gallons per day equals 1.55 second-feet.
1,000,000 United States gallons equals 3.07 acre-feet.
1,000,000 cubic feet equals 22.95 acre-feet.
1 acre-foot equals 325,850 gallons.
1 inch deep on 1 square mile equals 2,323,200 cubic feet.
1 inch deep on 1 square mile equals 0.0737 second-foot per year.
1 foot equals 0.3048 meter.
1 mile equals 1.60935 kilometers.
1 mile equals 5280 feet.

1 acre equals 0.4047 hectare.
1 acre equals 43,560 square feet.
1 acre equals 209 feet square, nearly.
1 square mile equals 2.59 square kilometers.
1 cubic foot equals 0.0283 cubic meter.
1 cubic foot of water weighs 62.4 pounds approx.
1 cubic meter per minute equals 0.5886 second-foot.
1 horse-power equals 550 foot-pounds per second.
1 horse-power equals 76 kilogram-meters per second.
1 horse-power equals 746 watts.
1 horse-power equals 1 second-foot falling 8.80 feet.
$1\frac{1}{3}$ horse-power equals about 1 kilowatt.

To calculate water power quickly: $\frac{\text{sec.-ft.} \times \text{fall in feet}}{11}$ net horse-power on water wheel realizing 80 per cent of theoretical power.

CHAPTER III

DAMS AND HEADWORKS

1. DAMS

Classification. Dams may be classified according to the material used in their construction, as:

Timber crib dams.
Earth-fill dams.
Rock-fill dams.
Masonry dams.

The choice of type is generally dictated by natural conditions. Solid rock foundations usually mean masonry dams, whether of overflow type or not. Absence of rock foundations, however, usually means the choice of crib, earth or rock-fill dams, and the choice between these is generally determined by local conditions, such as available construction material, etc.

Location. Before a final decision can be reached as to the exact location of a dam, there are numerous points which must be carefully investigated. For example, the value of storage available and the extent of land and property to be flooded. These factors affect the quantity of water which may be utilized, and the height of the dam, and therefore have a direct influence upon the amount of power which may be produced.

The character of the foundation material is of vital importance, being, in fact, a determining feature. The material must have ample bearing capacity for the loads imposed, and it must be impervious, or of such nature that it can be made so by artificial means. It should be thoroughly explored by test pits and borings, to determine its suitability for foundation purposes.

Available material for construction, such as rock, sand, etc., is also a deciding factor, as are also the facilities for spillways and channels to take care of the flood discharge.

It is, therefore, evident that the location can only be determined after a careful consideration of all the above facts. Comparative estimates are often required for a number of sites before the problem

can be intelligently solved, both from a technical and economic standpoint.

Timber Crib Dams. These dams are only used for low heads of about 30 feet and less and in locations where timber is plentiful and cheap. They are frequently used for diversion purposes. They are, however, often used for temporary structures or when the cost of other types would be prohibitive for the development in question.

They consist of a crib or framework of logs or sawed timbers, bolted or otherwise fastened together, the structure being filled with rock, gravel, earth, etc., and the sloping sides are faced with planks to prevent leakage.

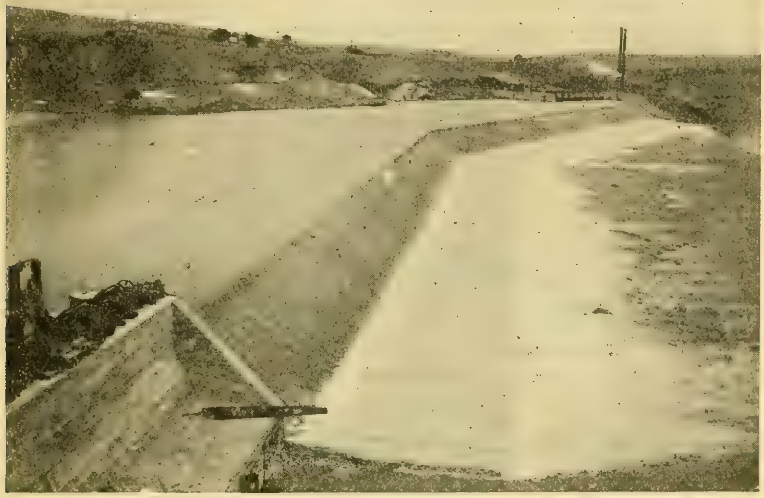


Fig. 27.—Timber Crib Dam, Montana Power Company.

Almost any kind of foundation may be used if the proper precautions are taken. With solid rock the framework should be securely bolted thereto to obviate any tendency of the dam to slide.

Soft foundations usually require a dam with wider base, and it may be necessary first to fill in with rock or gravel, while if the soil is pervious sheep piling may also be required. Undermining should also be guarded against by extending the facing at the toe and by employing steel piling.

Figures 27 and 28 show a rock-filled crib dam of modern design. The upstream side has been given such a slope that the stability of the dam is assured even under the greatest floods, the weight of the water acting to hold it down, so that the higher the flood the greater the

stability. The downstream side is also sloping and tapers off into a long apron, so designed as to take care of the overflow without chock or commotion. A sluiceway is provided at one end of the dam, and at the other there is a concrete chamber or forebay serving as intake to the pipe lines supplying the plant. The openings to this forebay are controlled by gates and are provided with the usual screens for the exclusion of trash.

Earth-fill Dams. This type of dam generally has a trapezoidal cross-section and consists, as the name implies, of an earth-fill faced with some harder material. It cannot be overturned, and its stability depends on the imperviousness of the material used in its construction. It is not intended to be used as a weir, and in case of overflow is liable to be disintegrated and washed away. For this reason, earth-fill dams must be protected against overflow by spillways of suitable capacity. This type of construction is not intended for very high dams, and while

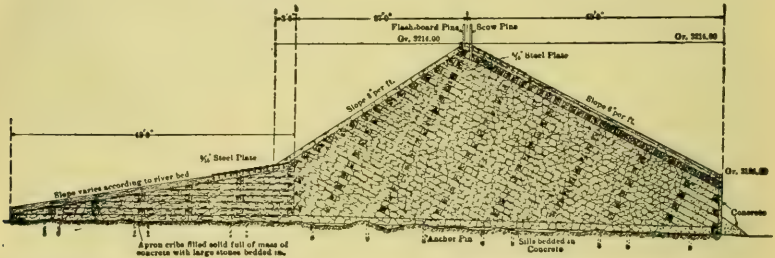


Fig. 28.—Cross-section of Timber Crib Dam Shown in Fig. 27.

dams of this type have been built for heights above 100 feet, about 50 and 75 feet is more common. There are no definite rules laid down for calculating the dimensions, but it is considered good practice not to let the slope of the wetted side exceed 1 in 3, while the outside slope may be 1 in 2. The structure should be at least 10 feet higher than the high-water level, and the width of the crest varies anywhere from 8 to 10 feet for low dams, to 20 or more for the highest one.

One of the most important things in its construction is to secure a water-tight foundation. Hardpan and clay are good foundations, while soft soil and rocks with fissures are very bad. The site must be cleared of tree stumps, roots, etc., and it is always necessary to remove the soil for a depth of 1 to 2 feet. One or more trenches are dug parallel to the axis of the structure, to hold the material; and if the soil is pervious it may be necessary to provide a puddle core, as shown in Fig. 29, in order to prevent the water from seeping under the dam; or piling may have to be driven down to bedrock.

The material which goes into the structure must be found near the dam site, and its character, therefore, determines the design and method of construction to a great extent. The best material is a mixture of gravel, sand and clay, and if this is readily obtained, the structure is generally homogeneous, as in Fig. 30.

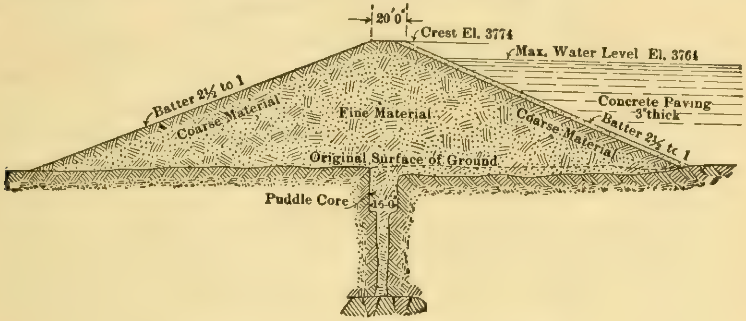


FIG. 29.—Earth-Fill Dam with Puddle Core.

There are many different methods of placing the material, such as providing trestles and dump-cars, cable ways, etc. If the material is taken from a higher elevation than the dam, and water is plentiful, the hydraulic method of filling may be used and is generally found very economical.

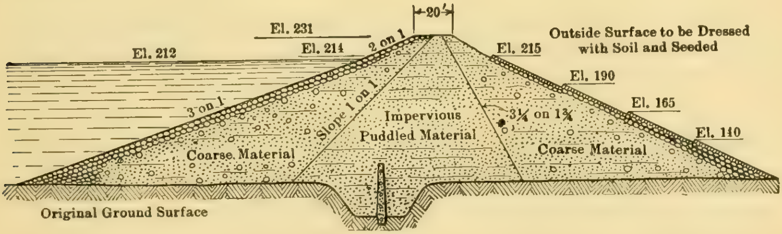


FIG. 30.—Earth-Fill Dam with Impervious Puddle Core.

If good material is not to be found near the site, puddle or concrete cores must be built to insure an impervious structure, as shown in Fig. 30.

Such a puddle core is preferably made of a mixture of clay and gravel, this being considered superior to clay alone. It is placed in the center, with the finer material next and the coarser outside. It should be protected from becoming dry, in which case it would crack and permit the water to seep through. Enough water is generally percolating through the structure to keep it moist. The fill towards

the outside surface should, however, be kept as dry as possible to keep it from disintegrating, and it is, therefore, advisable to install an efficient drainage system on this side.

To protect the wetted side from the effect of the water, it is usually constructed with a rip-rap paving, and sometimes a concrete facing may be advisable to prevent erosion. The other side should also have a covering of rip-rap or gravel, or it should, at least, be sodded.

Rock-fill Dams. A typical construction of this type of dam is shown in Fig. 31, the essential difference between the same and an earth-filled dam being found in the rock-filled part which forms the down-stream section, while the other side is filled with earth and gravel.

The rock-fill serves as a support for the earth-fill, which makes the dam impervious, and it is, therefore, evident that this type is superior to the plain earth-filled type, in that less damage would be caused by an overflow.

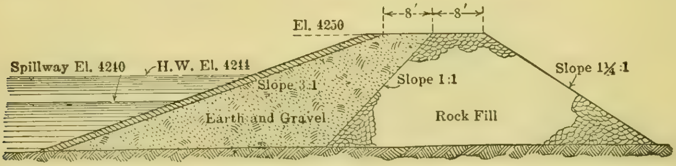


FIG. 31.—Rock-Fill Dam.

If only poor material can be obtained for the earth-fill, it is necessary to provide a puddle or concrete core, the same as with the previous construction, and the wetted surface should also be protected by a rip-rap or concrete facing.

Masonry Dams. Masonry dams may, according to their design, be divided in two general classes, gravity dams and arched dams. These may be further divided into solid and buttressed structures.

Gravity Dams. Gravity dams must resist any tendency toward sliding or overturning.

Assume a dam structure of a trapezoidal cross-section and with the water surface level with the crest, as in Fig. 32. Then the pressure in pounds acting on the up-stream side of the dam per foot length is equal to

$$P=\frac{62.4\times H^2}{2}\times \text{sec. } \theta.$$

Where

H = Head in feet;
θ = angle of dam surface with the vertical;
62.4 = weight of 1 cubic foot of water.

This pressure acts perpendicularly to the surface bc at a point two-thirds the height of the dam, figured from the top. The leverage with which this force tends to overturn the structure about point d is equal to the perpendicular distance between this point d and the continuation of the pressure line P, i.e., dk. The overturning force is, therefore, equal to $P \times dk$ foot-pounds.

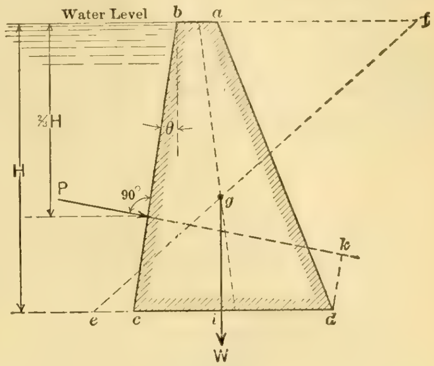


Fig. 32.—Cross-section of Gravity Dam (Water same level as crest).

The overturning force must be counterbalanced by the weight of the structure. This is equal to W and it acts perpendicularly from the center of gravity. Its leverage about the point d is equal to di and the resisting force is, therefore, equal to $W \times di$ foot-pounds.

The center of gravity of a trapezoid may be found graphically as follows: Draw af equal to cd and ec equal to ab. Divide ab and cd in two equal parts and connect the dividing points. Connect e and f, and the point where these two lines intersect is the center of gravity. It may also be calculated from the following formula:

$$gi = \frac{H}{2} - \frac{H}{6}\left(\frac{cd - ab}{cd + ab}\right).$$

The cross-section A of the dam can be figured from the formula:

$$A = H \times \frac{ab + cd}{2} \text{ sq. ft.},$$

and by multiplying this by the weight of masonry, 150 lbs. per cu. ft., the weight of the dam per foot length is obtained.

The factor of safety against overturning S of the structure is:

$$S = \frac{W \times di}{P \times dk}.$$

It is seen that the greater the inclines of the surfaces the more stable will the structure be.

In the above it was assumed that the water was level with the crest

of the dam. Suppose now that the water is flowing over, as in Fig. 33. In this case the pressure P is equal to

$$P=62.4\left(\frac{H+h}{2}\right)(H-h)\times\sec\theta=62.4\left(\frac{H^2-h^2}{2}\right)\sec\theta\text{ pounds.}$$

This pressure, however, is not applied at a point $\frac{2}{3}H$ from the top, as in the previous case, but at a point x from the top, this distance being equal to

$$X=\frac{2}{3}\left(H+\frac{h^2}{H+h}\right).$$

The resisting moment due to the weight of the structure is figured as in the previous case, except that the weight of the water should also be considered. The factor of safety, S, is found from the same formula as before, i.e.,

$$S=\frac{W\times di}{P\times dk}.$$

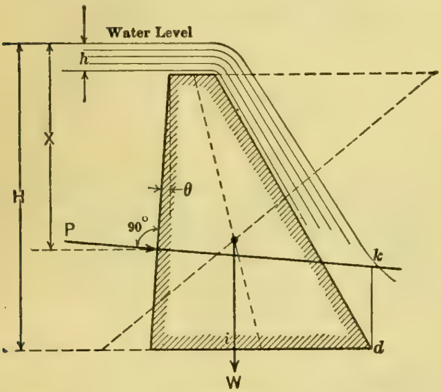


FIG. 33.—Cross-section of Gravity Dam (Water overflowing).

It is also common practice to ascertain if the design is safe by completing the pressure diagram, as in Fig. 34. The two forces P and W are scaled off from the intersection point X, and if their resultant P_1 falls inside the middle third of the base, the dam will safely withstand the overturning moment.

It is not sufficient, however, to determine the overturning moment for the full cross-section about the toe. It must be figured for several sections, such as a, b, c, d; a, b, e, f, etc. (Fig. 34), and the calculations must show that every part of the structure is sufficiently thick to withstand the pressure.

Besides the above, there are other stresses which must be given due consideration, such as ice thrust, uplift caused by seepage waters and internal stresses due to varying temperature conditions.

According to Mr. A. C. Beardsley, masonry dam design should be governed by the following rules:

1. Design the crest and apron so that vacuums cannot form.
2. Underdrain the dam to eliminate all uplift.
3. Design the toe of the dam so there will be no uncertainty as to the exact location of the tipping edge.

4. Allow for the effect of floating due to tail-water.

5. Allow for ice expansion and use the maximum crushing strength of ice instead of average values.

6. Take care of expansion and contraction stresses.

7. Allow for wave action.

8. Where necessary, reinforce the dam with steel.

On account of their great weight, gravity dams should necessarily be placed on bedrock foundations, and the materials should be carefully tested as to their bearing power. The fact should also be kept in mind that the pressure is not uniform over the entire base, but varies according to the water level back of the dam. For example, with the reservoir full, the pressure is, of course, a maximum at the toe and decreases toward the other side. All tendency to seepage should be prevented by sealing all fissures, and drains should be provided for carrying any waters that may reach the interior of the structure.

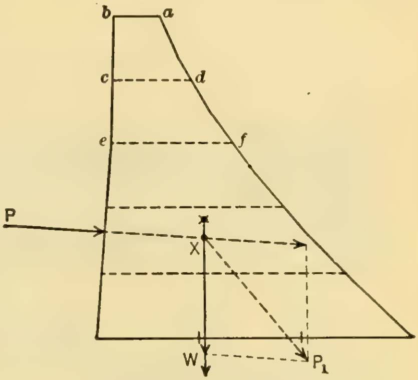


Fig. 34.—Graphical Determination of Safety of Gravity Dams (Middle-third method).

The material of which gravity dams are built consists either of concrete or rubble masonry. With the former, the rocks are crushed to a uniform size, making an even mixture, while with the rubble masonry, or cyclopean concrete construction, as it is also termed, large stones, weighing up to ten tons, are used. These are carefully placed in position and the spaces between them filled with smaller stones and cement mortar, forming a very strong structure.

The illustrations in Figs. 35 and 36 show a typical design of a masonry dam of the straight gravity type.

Buttressed Dams. This type of gravity dam has been devised with a view to utilizing the material more economically than is sometimes possible in a solid structure, a typical design being illustrated in Fig. 37. As seen, it is a hollow structure consisting of a concrete deck supported at stated intervals by buttresses or piers perpendicular to the axis of the dam. As the downward pressure of the water is relied on to a great extent to give the structure stability, the upstream face should have an incline of not more than 45° with the horizontal. The thickness of the deck should be proportioned in accordance with the

hydrostatic pressure, and it should vary uniformly from the base to the top, being sometimes reinforced with steel to increase its strength. Careful precautions should be taken to make the structure water-tight, and drains, as well as passageways for interior inspection, should be provided.

This type of dam requires very good foundations. As the entire pressure must be withstood by the buttresses alone, it is evident that the base width of these at right angles to the axis will have to be considerably greater than for a gravity type structure.

FIG. 35.—Typical Masonry Dam of the Gravity Type. Appalachian Power Company.

Arched Dams. These may be either of solid or buttressed design, curved in a horizontal arch with the abutments braced in the rock on the sides of the gorge or canyon, thus giving the required stability. It is not considered good practice, however, to rely entirely on the arch action; as a rule, therefore, dams of this class are designed as a combined arch and gravity type. In fact, the dam is often designed purely as a gravity structure, and the added strength given by its curved form is simply assumed to increase its safety to that extent. Figs. 38 and 39 illustrate an arched dam.

The multiple-arched dam (Fig. 40) has recently come into prominence, and gives promise of quite considerable reductions in the material required for buttressed structures spanning gaps of almost any width.

Spillways. In most low- and medium-head developments where large flood discharges must be passed, the entire dam or a large part of it must be built in the form of a spillway. It is important that the size of the spillway be sufficient to take care of the largest known floods; in order to be on the safe side, it is in many instances designed for 10 to 15 per cent greater discharge capacity than any previous record would show to have taken place. The downstream face should be curved, so that the water will follow the surface and prevent the

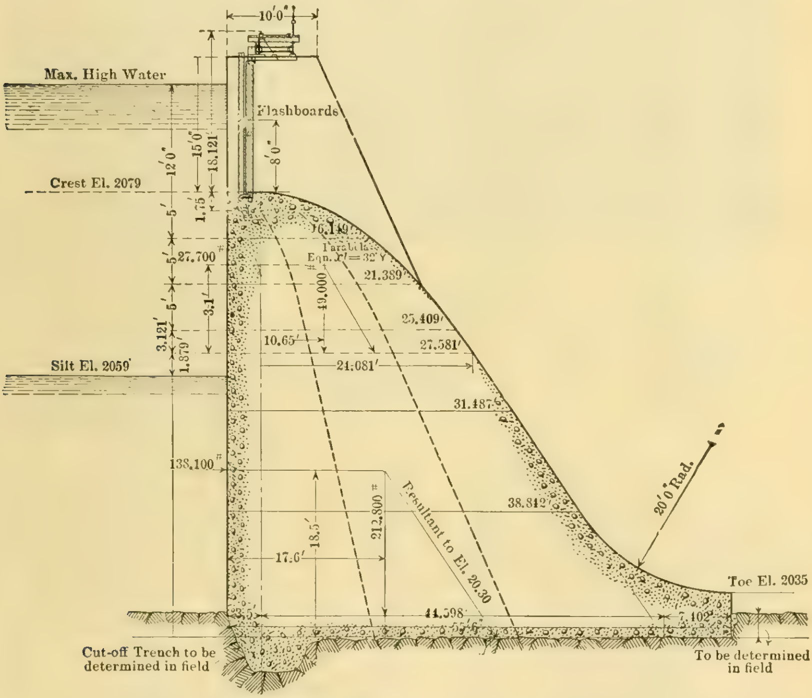


FIG. 36.—Cross-section of Masonry Gravity Dam Shown in Fig. 35.

formation of a vacuum. This curve will also cause the water to be discharged in a horizontal direction, protecting the bed of the stream against undercutting and erosion at the lower end of the toe when severe floods are passed, and permitting a quiet discharge without subjecting the masonry structure to dangers from vibrations.

With the common spillway, the rate of discharge per unit length depends on the depth of water on the crest, increasing as the depth increases; an overfall spillway may therefore not have much discharge capacity until the water surface rises to a considerable height. Such

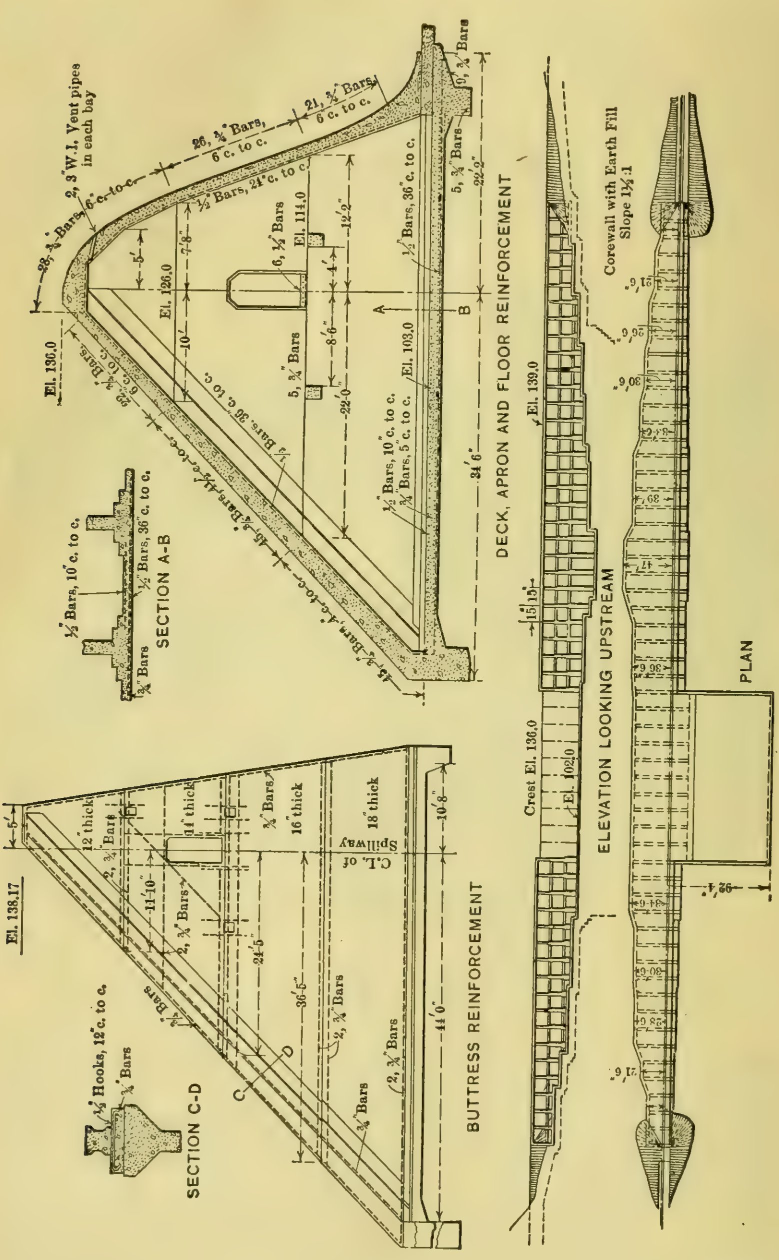


FIG. 37.—Straight Buttressed Dam.

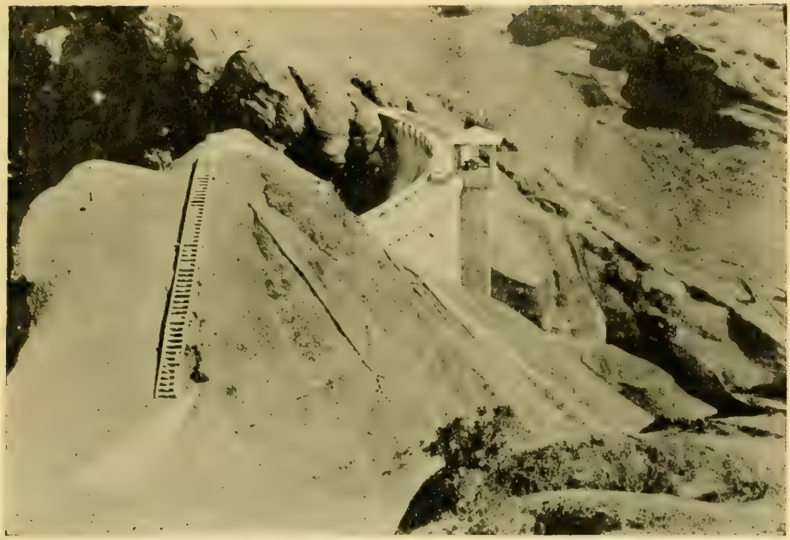


FIG. 38.—Arched Dam. Orland Project, California.

a spillway is not immediately responsive to variations in the stream flow, and does not closely control the water level.

In order, therefore, to increase the discharge capacity, the head must be increased, thus giving the water greater velocity; this is the principle upon which the *siphon* spillway is based. It consists of passages through the dam, as shown, in an elementary form, in Fig. 41, the lower end of the siphon, on the downstream side, generally being submerged. If the air is exhausted from the siphon, the maximum head available, being the total head between the water surfaces above and below the dam, will be useful, and a rapid flow will take place; the air will be automatically forced out of the siphon as soon as the

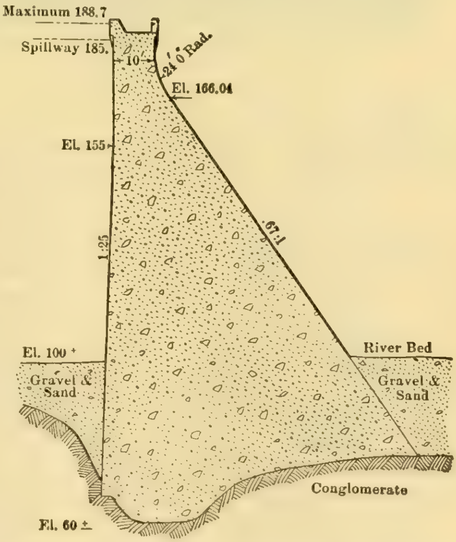


FIG. 39.—Cross-section of Arched Dam Shown in Fig. 38.

upper water level rises above the air vent, sealing it against the admission of air. The water will then spill over the crown of the siphon, forming a diaphragm of water which seals the upper part of the siphon

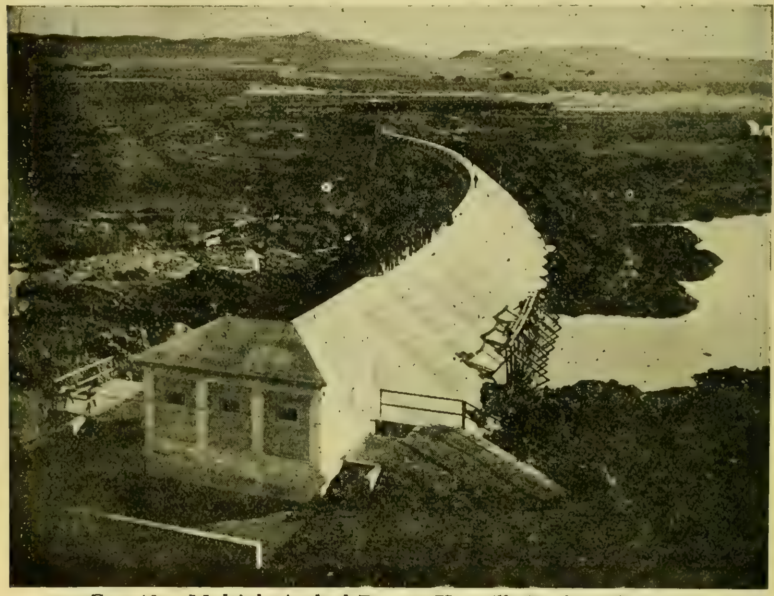


Fig. 40.—Multiple-Arched Dam. Umatilla Project, Oregon.

against the entrance of air from below. As the flow increases, all the air will be rapidly forced out, and the crown and siphon completely filled with water. The siphon will then be in full action and will keep on discharging until the upper water level is brought down far enough to unseal the vent, when air will rush into the crown of the siphon and break the siphonic action, and the flow will abruptly cease.

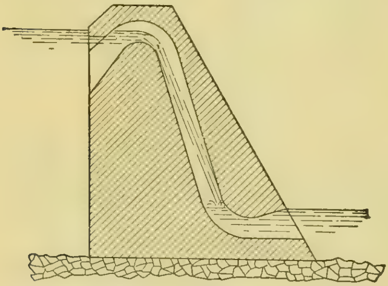


Fig. 41.—Elementary Form of Siphonic Spillway.

Dams with Backwater Suppressors. An ingenious method for maintaining the head during flood periods, by removing the high tailwater from the discharge openings, is described by John A. Sirnit in an article in the *Electrical World*, for June 10, 1922. This method involves an entirely new principle of construction, which is to be embodied in the Mitchell Dam on Coasa River, Ala. The device is known as the

Thurlow backwater suppressor, after its inventor, O. G. Thurlow, Chief Engineer of the Alabama Power Co., who conceived the idea of utilizing the waste water to remove the high tailwater.

Figure 42 shows how the energy of the overflow spillway water is directed so as to remove the backwater from over the draft-tube openings, sweeping the backwater downstream and thus freeing the draft tube from the pressure over it. A practically uniform head on the turbine is thus maintained, as long as the spillway water is able to sweep the backwater away from the draft tube orifices.

This type of construction necessarily involves radical departures from conventional plant designs, as seen from Fig. 43, which shows a cross-section through the power-house at Mitchell Dam. In order to provide a path for the overflow water, each power unit is independent and located on separate foundations, on the upstream side of the dam, so that no part of the spillway section is obstructed. The usual power-house building is entirely eliminated, the generator rooms being covered by a low roof, which is built in two sections mounted on rollers. This roof can be readily opened in case it becomes necessary to handle any of the heavy machinery by means of the gantry crane, which has a travel over the entire length of the power-house section.

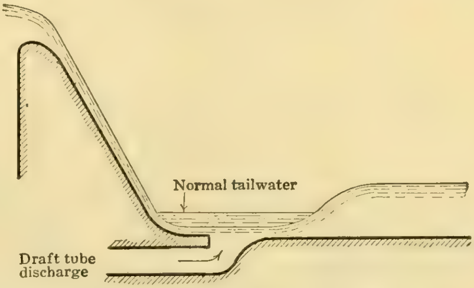


Fig. 42.—Diagram Showing Action of Overflow Spillway Water on the Tailwater.

General Rules Governing Design of Dams. The following are regulations governing the design and construction of dams as issued by the New York State Conservation Commissions:

"Complete plans, elevations and sections of all proposed dams must be submitted and approved of by this commission before any work on the dam can be commenced, and the site must be examined and approved of by this commission, both before and after it has been prepared.

"*Foundation Bed:* Dams must be built upon a firm, compact, impervious and natural foundation bed, from which all perishable material has been removed. Earth foundation beds must be ploughed or trenched. Masonry must be carried into solid rock at the base and sides, wherever practicable, and also have channels cut into the rock bed sufficient to afford a firm hold for the dam. Rock foundations

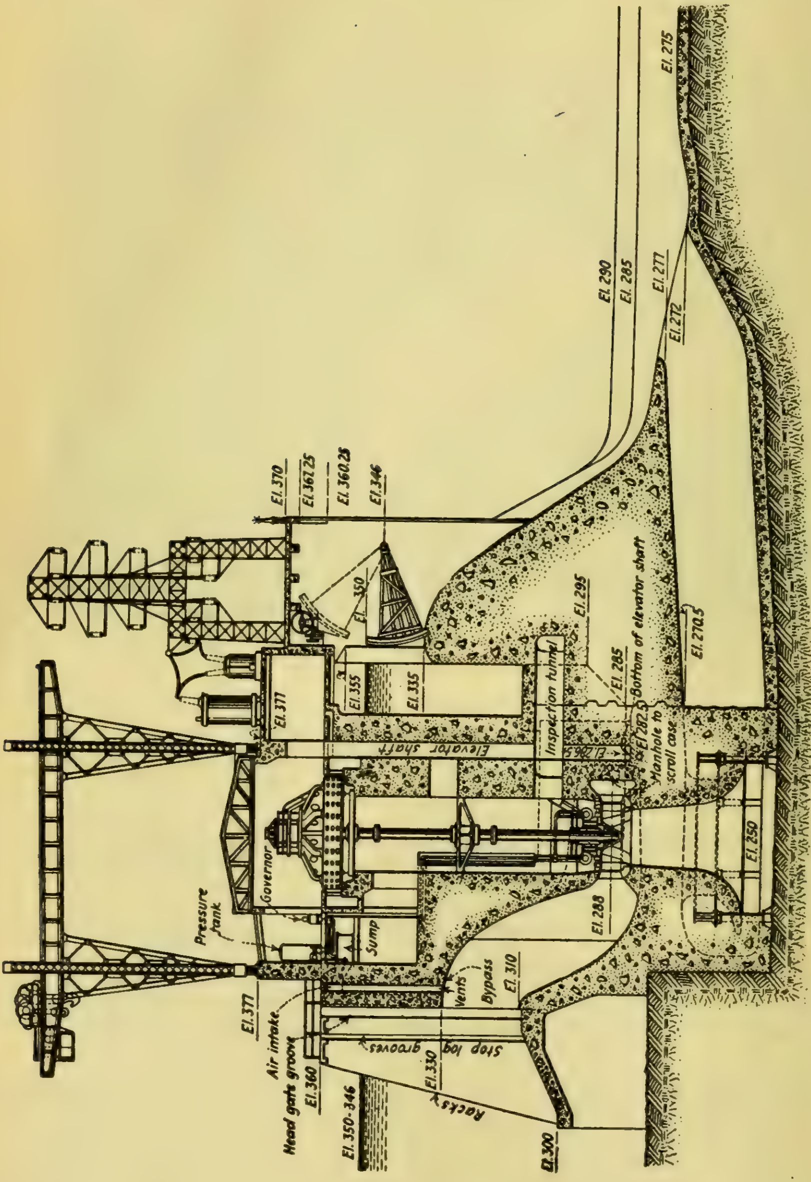


FIG. 43.—Cross-section through Power House of Alabama Power Company, Mitchell Dam, Showing Backwater Suppressor Arrangement.

must have all loose material removed; the crevices for 200 feet above and for 100 feet below the dam, must be thoroughly filled with concrete or grout, and the whole surface under the dam thoroughly washed. Masonry dams over 35 feet in height must have the rock bed drilled for hidden fissures and tested by compressed air; these holes must be filled with grout under a pressure equal to the maximum ultimate pressure.

" *Calculations:* Dams must be stable at any section and under all conditions. The compression upon masonry on the upstream face shall be 10, 14 and 18 tons per square foot and for the downstream face 8, 10 and 14 tons per square foot, depending on the mass; the first for walls less than 12 feet thick and buttressed dams, and the last for solid masonry dams over 150 feet in height, with the best of work, done under the inspection of a competent engineer approved by this commission.

" All cement must be Portland and up to the standard of the New York City Building Law, tested as prescribed by the American Society of Civil Engineers, and must more than fill the voids of sand and stone mixed in the proportions as used. The sand and stone used for masonry must be sound and permanent, clean, hard, and not easily sheared or split.

" *Outlets:* All dams must be provided with approved outlets of sufficient size, and so located as to completely allow the impounded water to be released when desired or necessary, and precautions must be made to prevent leakage along the outlets.

" *Ice Pressure:* From Dec. 1 to March 15 no dam shall have the water higher than two-thirds the height of the dam, unless permission is granted by the Conservation Commission to keep the water above at a higher level. Dams liable to be full during the above period must be built strong enough to resist any possible ice pressure in addition to the water pressure, and dams not so designed must have an outlet at two-thirds the height of the dam.

"*Aprons:* Spillways of all dams must be provided with aprons or other provision on the downstream side to prevent the undermining of the dam by the falling waters.

" *Wooden Dams:* Wooden dams may be used for temporary purposes, or where the reach of the water impounded above the dam is not over 300 feet or its depth more than 10 feet. The timber of the dam must be removed at the end of five years, unless express permission is granted by the Conservation Commission for a longer period.

" The crib work of wooden dams shall be built in pockets not more than 8 feet square, well fastened together with at least $\frac{3}{4}$-inch spikes

or bolts, long enough to pass through three timbers, and the pockets solidly packed with stone. The upstream face is to be built at an angle of three horizontal to one vertical, covered with plank, on which is to be laid a good layer of gravel. If the foundation is rock, the bottom timbers must be anchored to the rock.

" *Earth Dams:* The upstream half of earth dams shall be composed of gravelly earth with about 15 per cent of clay, with no stones over 4 inches near the upstream face, or, if there be a core, next to the core on the upstream side. The earth is to be moist, not wet, well rolled in 12-inch layers slightly sloping down to the middle of the dam. The downstream half, or part below the core, may be composed of coarser materials and stones. The top should be slightly convexed and of a minimum width of 8 feet plus 1 foot in width for every 5 feet over 15 feet in height. The slopes should be two horizontal to one vertical, except if stone is used on the downstream half it may be one and one-half horizontal to one vertical. If the upstream part is of very fine material, the slope must be less. A berm, or horizontal surface, which shall be not less than 4 feet wide, shall be constructed on the slopes at every 20 feet horizontally from the top. On the downstream face these berms shall be provided with paved gutters. The upstream face shall have an 18-inch stone pavement laid in broken stone or gravel from the top to the upper berm, and below shall have a pavement of rip-rap. The downstream face is to be sodded or covered with 12 inches of gravel or rip-rap.

" Every earth dam must be provided with a masonry spillway of sufficient unobstructed area to take the high flow, and built with the same requirements as for masonry dams. The height of the dam shall be at least 3 feet above high flow, plus 3 feet for a reach, or expanse of water upstream, of one mile, plus 8 feet for a reach of two miles, and proportional for an intermediate reach.

" Earth dams of over 10 feet in height shall be provided with a masonry core in the middle, the top to be not more than 2 feet below the top of the dam, and a top width of not less than 2 feet with a batter of 1 horizontal to 24 vertical on each side. Or, the core may be placed on the upstream side, in which case the width of the core at any point must be equal to half of the depth. Or, the core may be omitted and the dam made 5 feet wider and 3 feet higher than above specified; in this case the hydraulic process of construction may be employed.

" *Masonry Dams:* The least width of masonry dams shall be one-tenth of the height, with a minimum of 4 feet. The minimum width at any depth shall be two-thirds the depth below the highest water level.

"The masonry must be built up in horizontal sections with center grooves in the top and sides for bonding, formed by embedding beveled timbers in the concrete. Concrete masonry shall have vertical cast-iron bars in the upstream face, placed at least 2 feet apart and of sufficient length to protect the masonry against ice and floating bodies.

"*Reinforced Buttressed Dams:* The buttresses shall not be over 20 feet apart for dams over 100 feet high on rock foundations, and nearer for others, with the necessary cross stiffening girders. The upstream face shall be at an angle of not over 45° with the horizontal and the downstream face not over 60°. No part of the dam shall be less than 12 inches thick.

"If the dam is on rock foundations, the front face must have a heavy cut-off wall built into the rock. If on gravel and clay foundations both faces must have deep cut-off walls and a heavy reinforced flooring with weep holes to relieve the water pressure under the flooring. Drainage must be provided in interior pockets for seepage waters, and, if practical, the interior must be made accessible to allow for inspection.

"The crest of the spillway, and for 3 feet below, must be thickened and heavily reinforced, and the entire dam and bulkheads protected from ice and floating bodies the same as masonry dams. The dam must be well anchored to the bulkheads."

2. FLASHBOARDS

The maintaining of a constant water level above the dam is naturally very desirable. This water surface fluctuates considerably during the different seasons of the year, depending on the flow, and it was previously shown that the spillway must be of ample capacity to discharge the flood waters and prevent the water above the dam from flooding such land as has not been included in the flowage area. It is furthermore desirable to keep the surface at approximately the same level during the low-water periods and thus maintain a constant head. This may be accomplished by providing flashboards, which are placed on the top of the dam, and arranged to be raised or lowered with the variation in the water level. It has also been found that, for installations with steam reserve plants, the operating arrangement that will insure the most efficient use of the river flow is to maintain the level in the storage reservoir at nearly the crest of the flashboards, letting the auxiliary plant carry any excess load until such time as reports from the watershed above indicate a freshet. Then the steam plant is shut down and the water drawn down in the reservoir to such an extent as to allow it to be filled by the anticipated freshet.

There are numerous designs of such flashboards, the most common being as follows:

1. Stationary flashboards.
2. Sliding gates.
3. Tilting gates.
4. Tainter gates.
5. Rolling gates.

All of these, with the exception of the first class, require that piers be provided on the crest of the dam, between which they may be supported. The number of these piers and spillway sections depends then on the maximum length to which the gates can be successfully built.

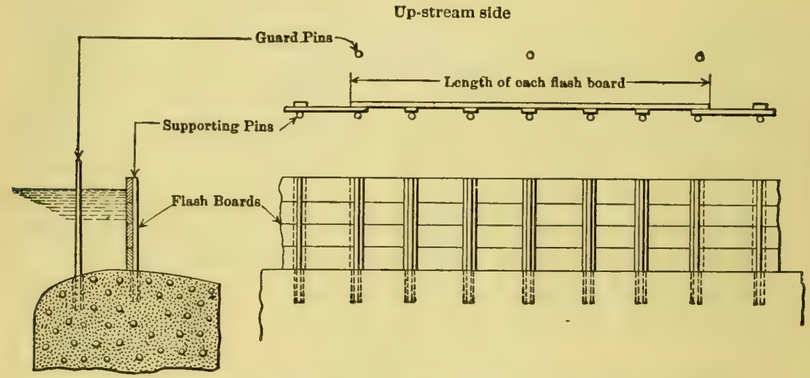


FIG. 44.—Stationary Flash-board Design.

Stationary Flashboards. This arrangement simply consists in placing a row of wooden panels on top of the dam crest, and supporting them by iron pins which are set vertically in holes previously provided in the concrete structure, as shown in Fig. 44. These pins are so dimensioned that when the water reaches a certain elevation they will give way and readily release the boards.

R. Muller (*Engineering Record*, August 22, 1908), gives the following formula for calculating the head of water that will cause the iron pins to bend. It is based on Wayne iron pins:

$$X=\frac{18.12d^3}{Sh^2}+\frac{2}{3}h;$$

in which

X = height of water in feet above the dam crest when pins begin to bend;
d = diameter of pins in inches;
S = spacing of pins in feet;
h = height of flashboard in feet.

The ends of the different sections overlap each other, as seen in the illustration, and a fairly water-tight joint is thus provided by utilizing the water pressure itself. For sealing the joint between the lower edge of the boards and the masonry it has been found that a composition of cinders and straw, well mixed before application, is very satisfactory. In it the cinders form the body, while the straw is the elastic tightening medium.

While the pins are ordinarily removed once a year, the flashboards are likely to be taken up a number of times each season, and speed and economy in their handling is, therefore, of importance. For wide streams the usual method of handling them is by means of a scow provided with a steam-driven derrick, while for narrower streams specially designed cableways with chain hoist have been used with very great success.

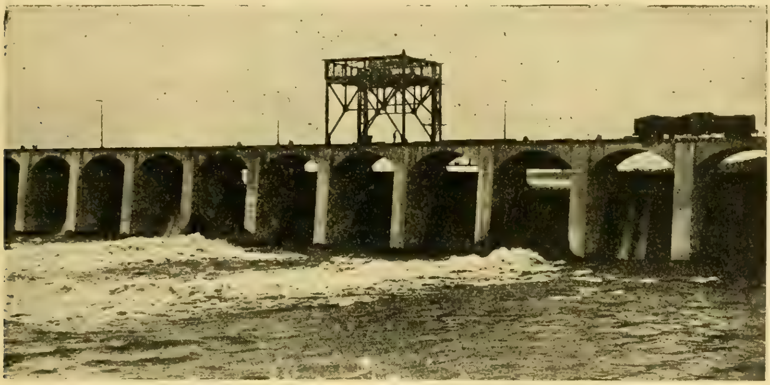


FIG. 45.—Spillway Gates. Mississippi River Power Company, Keokuk, Iowa.

Sliding Gates. These may either be of the plain friction type or may be provided with roller guides to make their operation easier.

The gates used by the Mississippi River Power Company at Keokuk, Iowa, shown in Fig. 45, indicate probably the maximum size to which the friction type can be built. They are 11 feet high and 32 feet long over all. Each gate consists of a framework of 18-inch I-beams, covered with $\frac{3}{8}$-inch steel plate on the upstream side. The edges are milled to make a water-tight joint with the iron sill plates against which they fit, and the gates are operated by an electrically driven crane running along the bridge, which forms the top of the dam.

For smaller installations, a much simpler structure, such as an ordinary hand-operated sluice gate, can, of course, be used. (See section on "Gates and Valves.")

A good example of the enormous size to which sliding gates with roller guides can be built is that of the Gatun spillway of the Panama

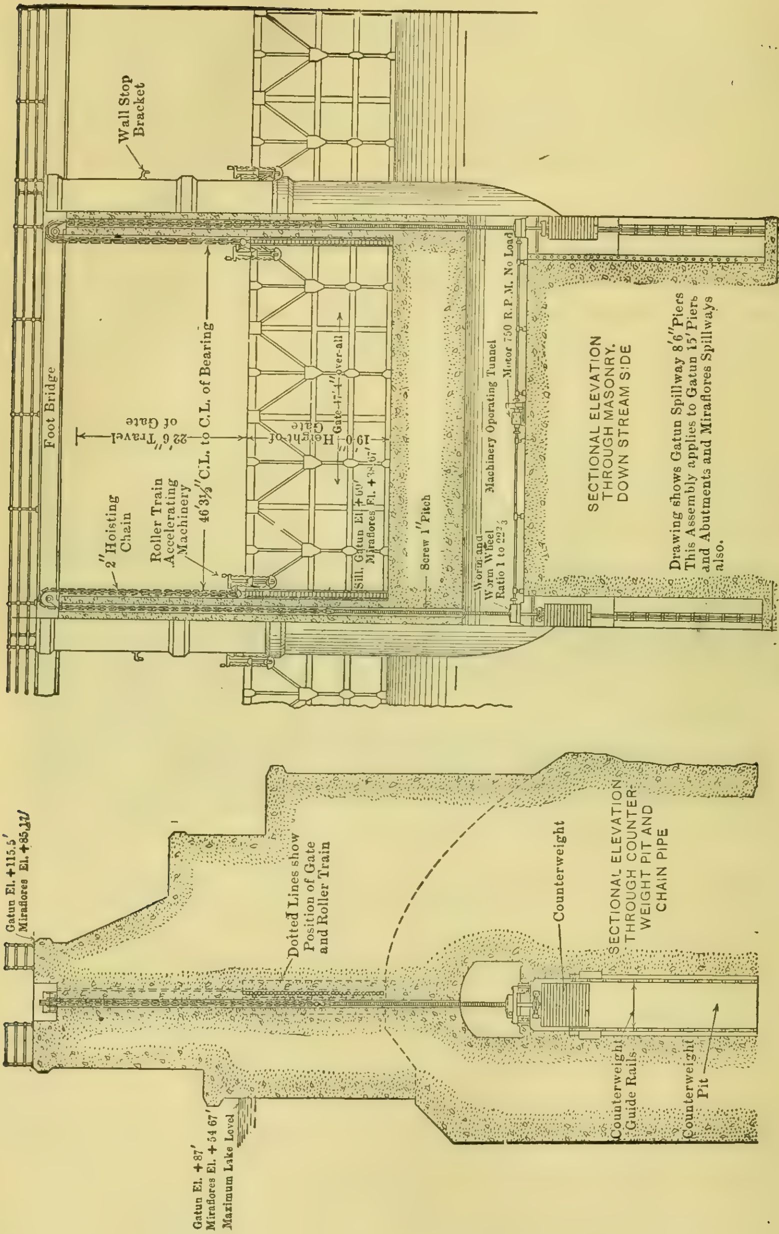


FIG. 46.—Spillway Gates at Gatun Dam, Panama Canal.

Canal, as shown in Fig. 46. Each of these gates has a height of 19 feet and an over-all length of 47 feet. The operating machinery is designed to raise or lower the gates in approximately ten minutes. It consists essentially of two counterweights, one at each end of the gate, which practically balance the weight of the gate, so that the machine has to overcome only the resistance to movement of the gate due to the water pressure. These counterweights are connected to the gate by a screw and chain, the screw being moved vertically by means of a worm nut, which is motor driven by a worm. The two screws at the gate ends are driven simultaneously through a driving shaft, which is provided with a worm at each end for operating the worm nuts. The screws are held in a vertical position and the hoisting chains pass over sheaves at the tops of the gate piers. A machinery tunnel extends the full length of the spillway, a distance of approximately 800 feet; it is built within the dam and contains all the operating machinery. Limit switches are provided to prevent overtravel by cutting off the current from the motor at the proper instant.

Tilting Gates. This type of flood gate generally consists of a flashboard which is hinged at its lower edge to the crest of the spillway, the other edge being free to move from a more or less vertical to a horizontal position. It maintains its upright position until the water level above the dam reaches the normal level. As the water continues to rise the additional pressure on the gate will cause it to tilt over further, until it finally rests in a horizontal position on the dam crest. As the water subsides the gate will automatically rise until the normal water level in the pond is reached.

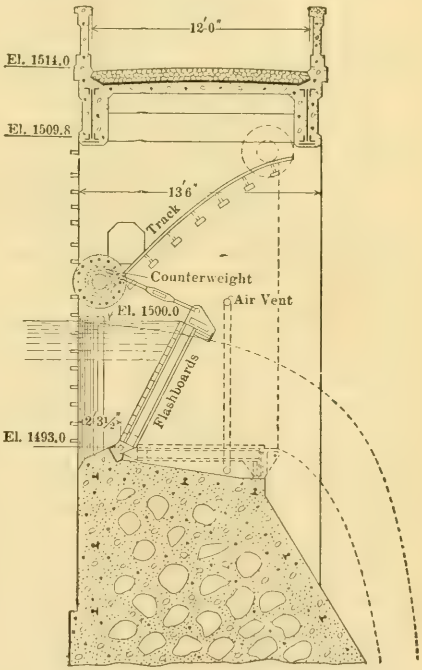


FIG. 47.—Tilting Spillway Gate with Counter Weight.

Many different devices have been used for accomplishing the counter-balancing effect, one of the latest being that shown in Fig. 47. This particular installation is designed to operate with a maximum fluctuation in water level of 3 inches.

Each flashboard consists of a steel-reinforced timber panel hinged at the bottom and connected at the top to a 17-ton concrete roller counterweight, by two steel cables, which are wound in grooves around each end of the roller. These rollers travel on inclined tracks, each end being provided with a geared drum which engages a rack to prevent slipping. The principle of operation is simply a balancing of the moments of force. The pressure on the flashboards is transmitted to the drums through the cables which act to roll the counterweight up the track, while its dead weight tends to roll it down; the two forces balance each other when the water level is at the fixed elevation. Hand-operated winches are also provided, and their general construction is clearly shown in the illustration.

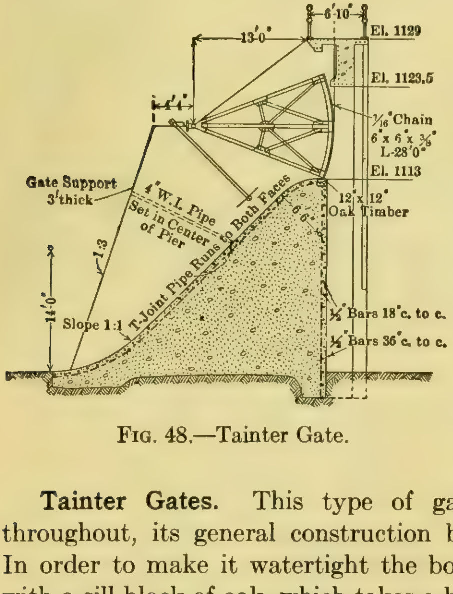


FIG. 48.—Tainter Gate.

The above dam consists of 10 spillway openings, 6 of which are provided with these automatic spillway gates. The other 4 openings, which are located towards the intake side, are provided with flashboards of the ordinary stationary construction, and are so designed that if the water in the pond rises 1 foot above the normal level, the boards will give away.

Tainter Gates. This type of gate is generally built of steel throughout, its general construction being clearly shown in Fig. 48. In order to make it watertight the bottom of the gate may be fitted with a sill block of oak, which takes a bearing on a steel plate set in the top of the concrete sill. Along the ends may also be fitted rubber strips for making a tight joint with the side walls.

The gates are usually raised and lowered by chains attached to the bottom edge of the gate and wound upon drums on a shaft above. They may be either hand- or motor-operated.

Rolling Gates. The principle of these gates is implied in the name; that is, the weir body is moved away from its closed position by rolling on an inclined track. In the simplest form it consists of a large hollow cylinder of a diameter corresponding to the height to which it is desired to raise the water, and of a length equal to the width of the opening to be closed. This cylinder is built up of boiler plate, substantially braced

to withstand the strains to which it is subjected. At each end the cylinder is provided with a specially designed gear engaging a rack laid in an inclined recess in the abutment or pier. By means of a sprocket chain wrapped around one end of the cylinder and connecting with the operating mechanism, the dam can be rolled up or down as desired. (See Figs. 49 and 50.)

For larger lifts and moderate spans, the cylindrical part of the weir is often much smaller in diameter than the height of the weir, the

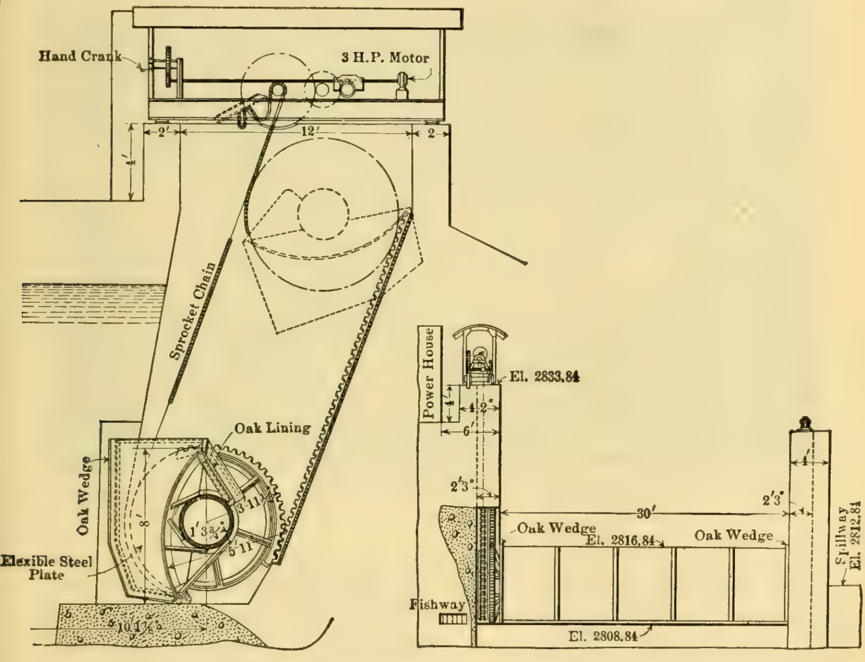


FIG. 49.—Details of Boise Roller Dam, Showing the General Arrangement.

upstream side of the gate being provided with a metal shield connected by strong braces to the cylindrical body.

This type of gate is a comparatively new invention and, while it has been used in Europe to a considerable extent, there are only a few installations in this country. It possesses many advantages over other types of flood gates on account of the larger size in which it can be built.

3. FISHWAYS

In many states, the law demands that dams be provided with means whereby fish can easily ascend and descend, according to their natural habits, in search of spawning grounds and of food.

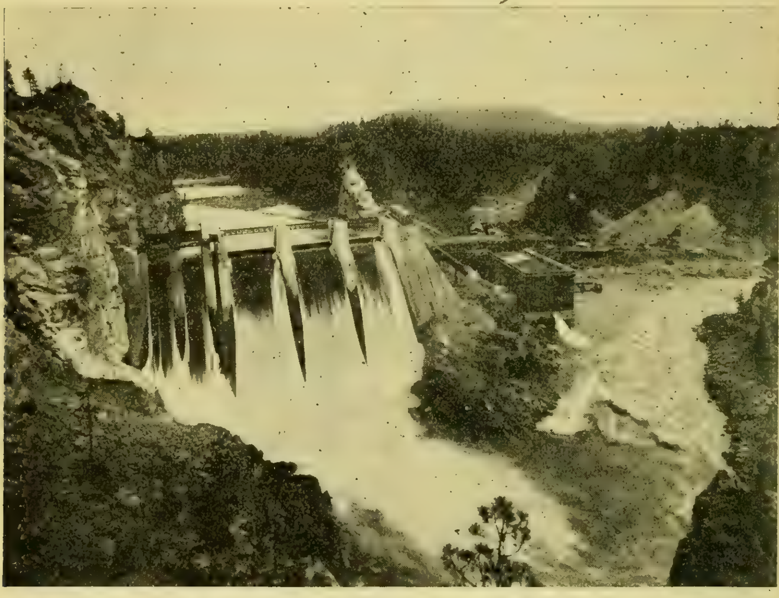


FIG. 50.—Dam of Washington Water Power Company, Showing Arrangement of Rolling Gates.

Many different designs, of more or less value, are in use, the illustrations in Fig. 51 showing fishway recommended by the New York State Conservation Commission. This type is termed the Improved Coil Fishway, and consists of a number of compartments arranged in steps and separated by cross-partitions. These are provided with orifices, alternating from side to side. The fish may pass through the orifices, from compartment to compartment, or may leap over the cross-partitions, according to their habit.

4. INTAKES

Intakes of many kinds are employed, and their design and location are governed, to a great extent, by local conditions.

Trash Racks. An essential feature which is common to all types and has a bearing on the economic use of water, is the trash rack and

its design. These racks should be so constructed as to give sufficient area for passing the desired quantity of water without excessive loss in head. This is especially important in low-head developments, where large quantities of water are utilized. Considerable loss of efficiency may result from restricted water passages through racks; and, in the design, allowance should be made for the accumulation of trash as a factor in the restriction of water passage.

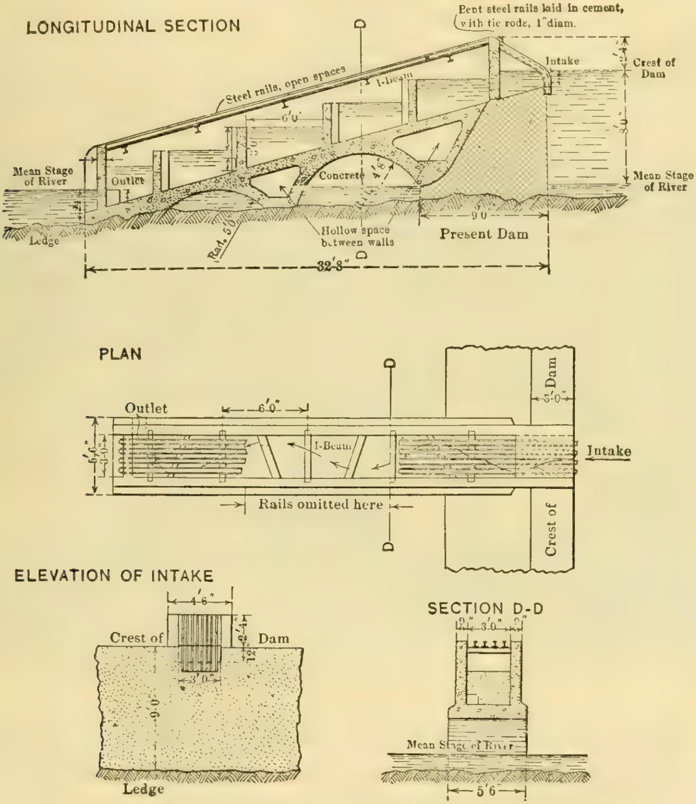


FIG. 51.—Fishway.

Low-head Installations. With low-head plants the intake generally forms a part of the dam or power-house, as shown in Fig. 11 in section on "Low-head Developments." The upstream bay comprises the gate room, and as the gates and screens are thus installed indoors, there is less danger from ice forming therein during cold weather. In certain stations, arrangements are also made whereby the heated air from the generators can be led to the gatehouse for preventing the formation of ice.

The water from the forebay is frequently made to enter the gate-house through arches in the front wall, and if these are submerged below the low-water level, certain floating material will be prevented from entering.

High-head Installations. For high-head plants the intakes are often built as independent structures, and where overflow diversion dams are used, they should preferably be located at a right angle to the dam. This arrangement has several advantages, among which are the

FIG. 52.—Tunnel Intake, Showing Its Relation to the Diversion Dam.

ease with which logs, trees and other floating debris can be cleared away by simply opening one or two of the nearest flashboards.

The intake shown in Figs. 52 and 53 represents a typical installation of a good design. It is a caisson-like, self-contained structure divided by partitions into five sections, in order to resist the stresses on the outside walls due to the hydrostatic pressure existing when the intake is empty and the water in the pond is at its maximum elevation. At the rear of each division wall there is an opening which allows the water to pass to the tunnel entrance located at the center and bottom of the rear wall.

There are two sets of racks, a coarse set, consisting of $\frac{5}{8}$-inch round iron rods spaced 4 inches apart, being placed in front of the head gates

to prevent large debris from interfering with their operation. In addition, there is a fine set mounted in an inclined position in each of the intake chambers. These racks are made of $4 \times \frac{3}{8}$-inch flat iron bars, spaced $1\frac{1}{4}$ inches apart. They are provided with a rack cleaner, each rack section being cleaned by three rakes placed in a staggered position and operated at a speed of 3 feet per minute by means of link chains from a motor-driven countershaft located on top of the structure. At the top of each bay, an adjustable iron comb catches the debris collected by the rakes and drops it on the floor.

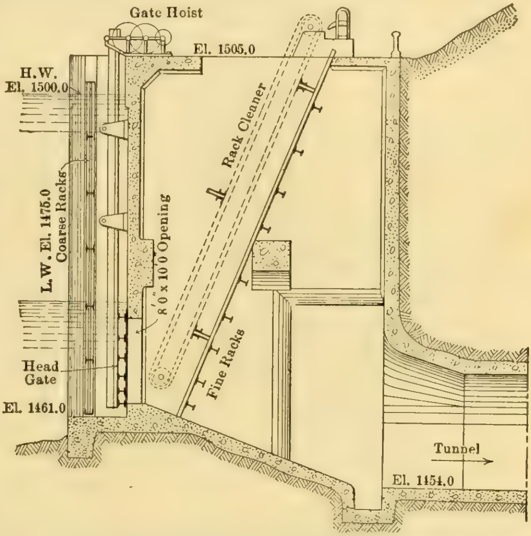


FIG. 53.—Cross-section of Tunnel Intake Shown in Fig. 52, Illustrating Racks, Rack-cleaners and Gates.

Submerged Conduit Intake. A submerged intake construction has been invented by P. Wahlman, Hydraulic Engineer, of New York City. The principal object of this is to provide a submerged conduit, or intake, capable of drawing large quantities of water from comparatively shallow lakes and rivers, which at times carry a great amount of floating ice. Under these circumstances, it is desirable to draw the water from near the bottom and from as large an area as possible, in order not to disturb the natural flow of the ice-carrying surface water. Such intakes are now in use at Niagara Falls and at Shawinigan Falls. They consist of a number of submerged concrete tubes extending several hundred feet out into the river from the intake dam.

Figure 54 shows the arrangement of such tubes for taking water from the Niagara River into the Welland Canal. The tubes in this case are 675 feet long, and each has a slot running from its small end for 500 feet of its length. The slot is on the upstream side, and varies in width from 1 foot at the shore end to 4 feet at the outer end, where a restricted section forms a mouthpiece to give the required initial impulse to the water.

Influence of Ice. In cold climates, where it is impracticable to

reduce the entering velocity of water to a sufficient extent to allow the surface to freeze over, and where considerable quantities of anchor or frazil ice are likely to be swept against the racks, adherence to the racks may be reduced either by maintaining the portion of the racks above the water surface at a temperature above freezing, by housing or otherwise, or by constructing the exposed portions of the racks of wood, concrete or other nonconductors of heat, the portion below the

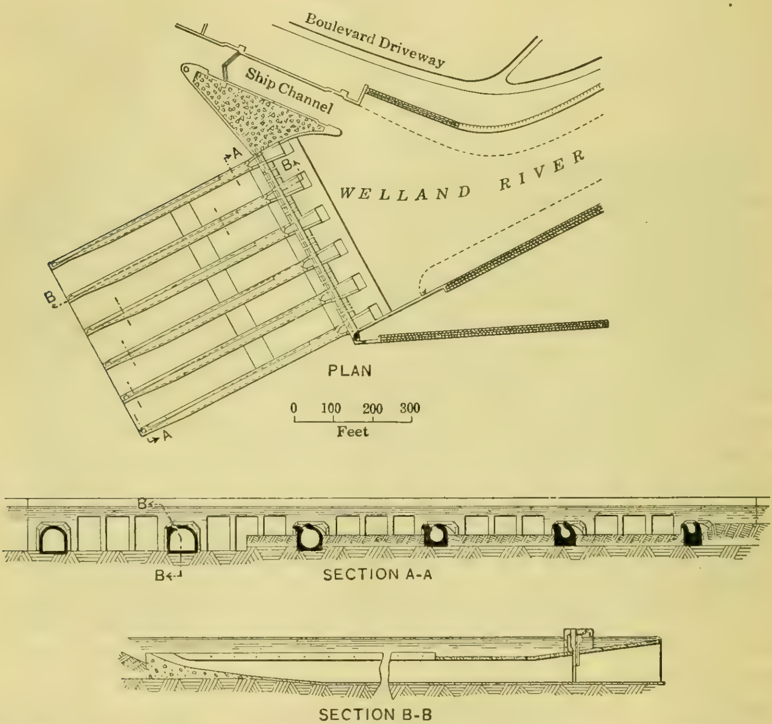


FIG. 54.—Submerged Intake Construction at Chippewa on the Niagara River.

water being of steel. Electric heaters have been used in some cases for the purpose of preventing clogging of the racks; and it has also been proposed to so arrange the bars composing the rack that a low-voltage electric current may be sent through them in series, thus heating them sufficiently to prevent the adherence of ice.

For further information on precautions to be taken against ice troubles, the reader is referred to the 1922 Report of the N. E. L. A. Hydraulic Power Committee. This report also contains a bibliography of the more important articles on this subject.

CHAPTER IV

WATER CONDUCTORS AND ACCESSORIES

1. WATER CONDUCTORS

Classification of Water Conductors. As in the case of dams, there is a great variety of types of water conductors, the particular kind to be used being entirely governed by the nature of the development, as well as by economy. Where the power-house is located near the dam, there may be no need for conduits at all, as in low-head plants, or they may simply consist of very short pipes. For medium- and high-head developments, however, a more elaborate system of conduits must, as a rule, be provided, as in many such instances the water must be diverted for miles, before it finally reaches the power-house.

The different kinds of water conductors in general use may be divided into two classes, open and closed; the closed construction being either of the low- or high-pressure type.

CLASSIFICATION OF WATER CONDUCTORS

- Open.
  - Canals: lined or unlined.
  - Flumes: wood, concrete or steel.
- Closed.
  - Low-pressure.
    - Tunnels.
    - Pipe: wood, concrete or steel.
  - High-pressure.
    - Pipe: steel.

Open canals and flumes are often used for carrying the water from the point of diversion to the beginning of the pressure lines. This method was extensively used in earlier developments, and while it may in many cases be the cheapest, a higher efficiency can be obtained by a closed system of tunnels and pipes, in that the total head will be greater. Where the contour of the country is very irregular, the cost of excavating for canals and of building high trestles for the flumes may be very high, and in such instances the closed construction generally becomes more economical, in that tunnels may be built and the pipes

TABLE XXVII

Table of *n* for Kutter's Formula

Surface.	Perfect.	Good.	Fair.	Bad.
Uncoated c.-i. pipe	0.012	0.013	0.014	0.015
Coated c.-i. pipe	0.011	0.012*	0.013*	
Commercial w.-i. pipe, black	0.012	0.013	0.014	0.015
Commercial w.-i. pipe, galv	0.013	0.014	0.015	0.017
Smooth brass and glass pipe	0.009	0.010	0.011	0.013
Smooth lockbar and welded "OD" pipe	0.010	0.011*	0.013*	
Riveted and spiral steel pipe	0.013	0.015*	0.017*	
Vitrified sewer pipe	0.010 0.011	0.013*	0.015	0.017
Glazed brickwork	0.011	0.012	0.013*	0.015
Brick in cement mortar; brick sewers	0.012	0.013	0.015*	0.017
Neat cement surfaces	0.010	0.011	0.012	0.013
Cement mortar surfaces	0.011	0.012	0.013*	0.015
Concrete pipe	0.012	0.013	0.015	0.016
Wood-stave pipe	0.010	0.011	0.012	0.013
Plank Flumes:				
Planed	0.010	0.012*	0.013	0.014
Unplaned	0.011	0.013*	0.014	0.015
With battens	0.012	0.015*	0.016	
Concrete-lined channels	0.012	0.014*	0.016*	0.018
Cement-rubble surface	0.017	0.020	0.025	0.030
Dry-rubble surface	0.025	0.030	0.033	0.035
Dressed-ashlar surface	0.013	0.014	0.015	0.017
Semicircular metal flumes, smooth	0.011	0.012	0.013	0.015
Semicircular metal flumes, corrugated	0.0225	0.025	0.0275	0.030
Canals and Ditches:				
Earth, straight and uniform	0.017	0.020	0.0225*	0.025
Rock cuts, smooth and uniform	0.025	0.030	0.033*	0.035
Rock cuts, jagged and irregular	0.035	0.040	0.045	
Winding sluggish canals	0.0225	0.025*	0.0275	0.030
Dredged earth channels	0.025	0.0275	0.030	0.033
Canals with rough stony beds, weeds on earth banks	0.025	0.030	0.035*	0.040
Earth bottom, rubble sides	0.028	0.030*	0.033*	0.035
Natural Stream Channels:				
(1) Clean, straight bank, full stage, no rifts or deep pools	0.025	0.0275	0.030	0.033
(2) Same as (1), but some weeds and stones	0.030	0.033	0.035	0.040
(3) Winding, some pools and shoals, clean	0.035	0.040	0.045	0.050
(4) Same as (3), lower stages, more ineffective slope and sections	0.040	0.045	0.050	0.055
(5) Same as (3), some weeds and stones	0.033	0.035	0.040	0.045
(6) Same as (4), stony sections	0.045	0.050	0.055	0.060
(7) Sluggish river reaches, rather weedy or with very deep pools	0.050	0.060	0.070	0.080
(8) Very weedy reaches	0.075	0.100	0.125	0.150

* Values commonly used in designing.

follow more or less the contour of the country. The selection of the particular type of conduit construction is, therefore, an engineering problem of considerable importance, and has to do with the economic operating features of the development.

Canals. The velocity of water in a canal is affected by the roughness of the bed, by the wetted surface of the form of the cross-section, and finally by the grade. According to Chezy's formula it is equal to:

$$v=c\sqrt{rs},$$

where v = velocity in feet per second;
c = coefficient;
r = hydraulic radius in feet;
s = grade or hydraulic slope.

The values of c may be obtained from the following two formulae, both of which are in common use.

Kutter's formula:

$$c=\frac{\frac{1.811}{n}+41.65+\frac{0.00281}{s}}{1+\frac{n}{\sqrt{r}}\left(41.65+\frac{0.00281}{s}\right)};$$

where n is the coefficient of roughness, the values of which are given in Table XXVII.[1]

Bazin's Formula:

$$c=\frac{87}{0.552+\frac{m}{\sqrt{r}}}.$$

TABLE XXVIII

VALUES OF m

Smooth cement and planed boards	0.06
Planks and bricks	0.16
Rubble masonry	0.46
Earth canals in excellent condition	0.85
Earth canals in fair condition	1.30
Earth canals in bad condition	1.75

The hydraulic radius, $r=\frac{\text{Area of Cross-section}}{\text{Wetted Perimeter}}$, the wetted perimeter of the cross-section of a channel being that part which is in contact with the water.

[1] R. E. Horton, "Engineering News," February 24, 1916.

For an open canal, the grade or slope, s, is the ratio of the fall to the length in which the fall occurs. For a closed penstock under pressure, it is the ratio between the loss in head due to friction to the length. (See also page 111.)

The velocity of the water in a canal should be kept below that which would cause erosion of the bed. It should, however, be large enough to prevent vegetable growth from forming and silt from being deposited. Assuming the bottom velocity to be about 75 per cent of the mean velocity, the figures in Table XXIX represent the safe values which are widely used in determining the permissible velocities of water in open canals.

TABLE XXIX

SAFE MEAN VELOCITIES *

Very fine sandy soil or loose silt	0.50
Pure sand	1.00
Light sandy soil, 15 per cent clay	1.20
Light sandy loam, 40 per cent clay	1.80–2.00
Coarse sand	1.50–2.00
Loose gravelly soil	2.50
Ordinary loam	2.50
Ordinary firm soil or loam, 65 per cent clay	3.00
Stiff clay loam	4.00
Firm gravelly clay soil	5.00–7.00
Stiff clay	6.00
Conglomerates, soft slate	6.50
Stratified rocks	8.00
Small boulders	8.00–15.00
Hard rock	13.33
Concrete	15.00–20.00

* B. A. Etcheverry, "Journal of Electricity, Power and Gas."

The most advantageous cross-section to use, from the hydraulic point of view, would be that which gives the smallest wetted perimeter or the largest value of the hydraulic radius. This would mean a semicircular section, but such sections are seldom used on account of the difficulties in building. A trapezoidal section is, however, generally used, and by letting the bottom and sides be tangents to an inscribed semicircle, as in Fig. 55, the best hydraulic results will be obtained; the slope, i.e., the angle θ, being 60°.

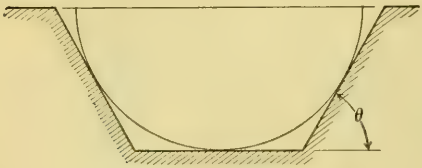


FIG. 55.—Cross-section of Canal.

The ideal cross-section from the hydraulic point of view is, however, not always the best to adopt. There are other factors which must be considered, such as the cost of construction, whether the canal is to be lined or unlined, the character of the soil, seepage, safety, grade, and velocity. No specific rules can be laid down to cover all cases, and each installation must be treated individually.

The concrete-lined canal having the least wetted perimeter will require the smallest amount of material, while the steeper sides mean less excavation. Furthermore, such a canal can be given a steeper grade, if sufficient fall is available, and thus a higher velocity, so that

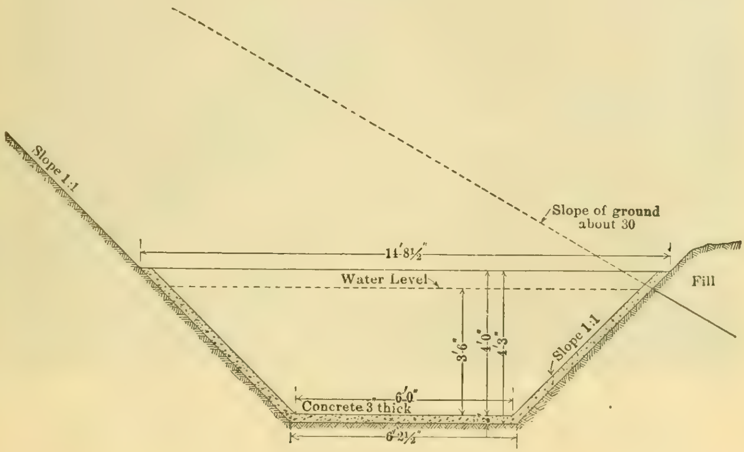


FIG. 56.—Open Concrete-lined Canal.

the cross-section can be small for a given quantity of water. This is advantageous, especially on hill sides; and, if the soil is hard and the excavation difficult, a concrete-lined canal may be cheaper than an unlined one. In other instances the soil may be of such a porous nature that lining is essential to prevent excessive seepage. (See Figs. 56 and 57.)

From the standpoint of safety, a shallow canal is better than a deep one. The pressure on the banks increases with the depth of water and may cause breaks, especially where canals are built on side hills, and where the banks may have been weakened by erosion.

The slopes should, therefore, in the first place, be such that they

NOTE.—For "Flow of Water in Channels," see Bulletin No. 194 U. S. Dept. of Agriculture.

will withstand such erosion of the water, the values given in Table XXX being representative of actual practice.

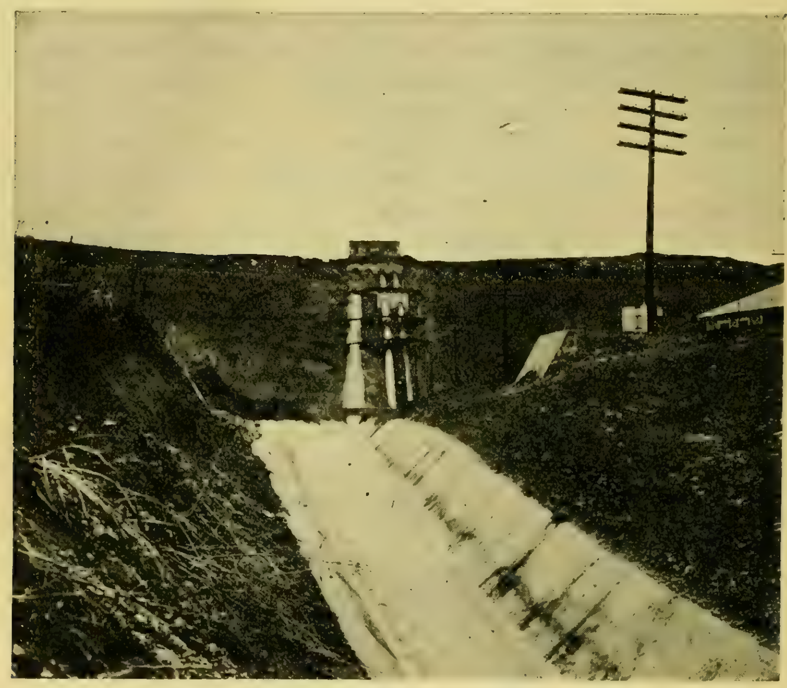


Fig. 57.—Concrete-lined Canal.

TABLE XXX

Side Slopes

	Horizontal.	Vertical.
Solid rock or cement	$\frac{1}{4}$–$\frac{1}{2}$	1
Hardpan and very firm soil	$\frac{3}{4}$–1	1
Ordinary firm soil	1	1
Ordinary sandy loam	1.5	1
Loose sandy soil	2	1

Evaporation is small as compared with seepage, which increases with the depth of the water and with the wetted perimeter, but decreases with an increase in velocity. Therefore, while evaporation can be neglected, the effect of seepage must usually be considered in determining the capacity of a canal.

The velocity decreases with an increase in the wetted perimeter, and when the fall is great it may be advisable to use a shallower section to reduce the velocity, or vice versa. If the actual slope of the country is so great that the corresponding velocities would cause erosion, it is necessary to limit the grade to a value which would not give an excessive velocity, and to concentrate the excess fall at suitable drops along the canal.

Flumes. Where the contour of the country is very irregular, or the soil very hard and difficult to excavate, flumes are sometimes used for diverting the water. While the first cost of such structures may be very low where timber is cheap, their upkeep is usually much higher than for a canal, and every precaution must, therefore, be taken in their design and construction.

The velocity of the water, which can be found from the formulae given in the previous section, may be much higher than for unlined canals, and the higher the velocity the smaller is the cross-section required. When the water, therefore, enters a flume from a canal, it becomes necessary to provide a sufficient drop in the upper end of the flume for the increased velocity head. This may be found from the formula:

$$h=\frac{v_1^2-v_2^2}{2g},$$

where h = drop necessary to increase the velocity in feet;
v_1 = velocity of flow in flume in feet per second;
v_2 = velocity of flow in canal in feet per second;
g = acceleration of gravity = 32.16.

Similarly, there should be a gain in head when the water again enters a canal from a flume, although this is not realized to a very great extent and can be neglected.

Flumes may be classified, according to the material of which they are built, as:

Rectangular wooden flumes.
Semicircular wood-stave flumes.
Reinforced concrete flumes.
Steel flumes.

They may also be classified, according to their general design, as bench flumes and trestle flumes.

A typical design of a rectangular wooden flume of the bench type is shown in Fig. 58, the width being from $1\frac{1}{2}$ to 2 times the depth of the

water. The illustration clearly shows the detail of construction. This type is used on hillsides or places where it may be located directly on the ground. When crossing depressions it is supported on trestles. Careful consideration must be given to the construction of the foundations, and precautions taken to make sure that floods will not undermine the same. Drains should, therefore, be provided if there is any such danger. Spillways for discharging any overflow should also be installed at points where the water can be readily disposed of. This refers to canals as well as flumes.

Figure 59 shows the design of a semicircular wood-stave flume. This section, as before stated, is very advantageous from the hydraulic point of view. It is easily adjusted to curves, and it can be kept water-

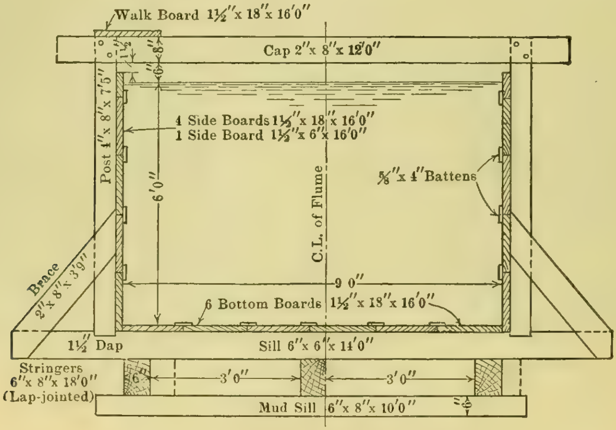


FIG. 58.—Rectangular Wooden Flume.

tight by screwing up the nuts above the tie-beams at the ends of each threaded band.

Reinforced concrete flumes have been used in some installations of late, Fig. 60 showing such a design. While the first cost is usually much higher than that of a wooden flume, the life of the concrete flume is so much longer and the maintenance cost so much lower, that it may prove more economical in the long run. A further advantage of such flumes is the omission of crosspieces over the top, which makes cleaning very easy. This point should be carefully considered for waters that are prolific in moss and vegetable matters.

Steel flumes are generally semicircular in cross-section, similar to Fig. 59. There are several makes of such flumes but their construction does not differ materially. They consist of curved metal sheets with a bead or corrugated groove rolled in each edge of the sheet. The sheets

are put together by means of an interlocking joint formed by overlapping the edges, which fit over each other. The joint is made tight by means of a curved rod which fits on the outside of the corrugated groove, and a curved beveled bar or small channel on the inside. The steel rods carry the weight of the flume, and their ends are threaded for nuts and

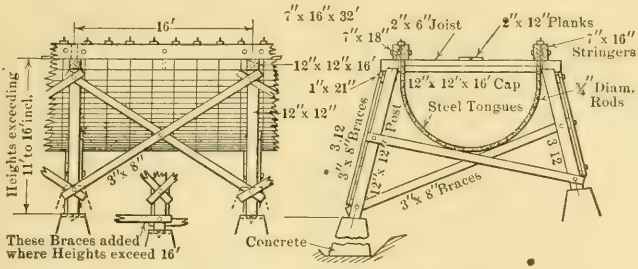


FIG. 59.—Semi-circular Wood-stave Flume.

pass through a carrier or tie-beam which is supported on stringers about 16 feet long.

As hydro-electric work becomes more permanent in character, and flumes are consequently used less and less, it is suggested that for preliminary estimating purposes the cost of low-pressure pipe lines be used instead of the presumably lower cost of flume construction.

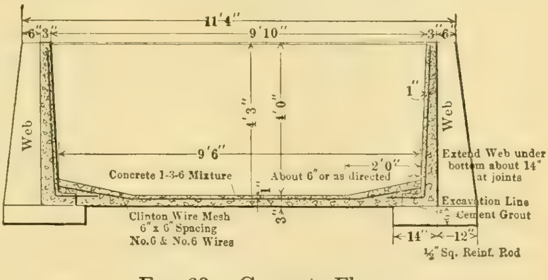


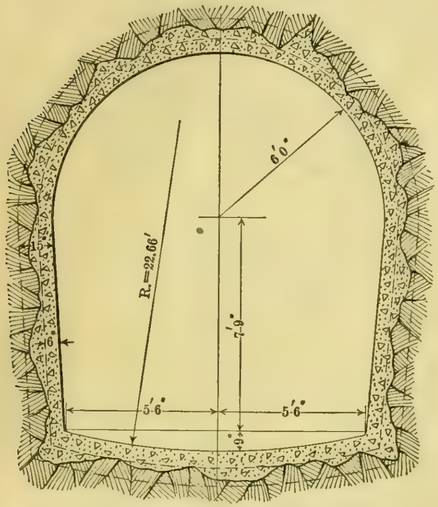
FIG. 60.—Concrete Flume.

Tunnels. Where the proposed route of the waterway encounters mountain ridges, it is often advantageous, if not absolutely necessary, to go through these by means of tunnels rather than to excavate deep cuts or go around. The question as to which method should be chosen is one of first cost as well as of maintenance. Tunnels are, of course, safer, and their upkeep is usually low as compared with open canals, especially if these are built on the hillsides where they are exposed to dangers from boulders striking them, undermining, etc.

Tunnels may be either of the pressure or non-pressure type. When of considerable length they are usually of the former type so that the drop may be utilized as useful head. They are almost always lined with concrete, the thickness of the lining varying from 4 to 12 inches

according to the grade and the pressure of the water. A lining serves several purposes. It holds the rocky material in place; it prevents seepage if the rock is porous; and finally it decreases the friction, which is of greatest importance in tunnel work, as it permits a higher velocity with a correspondingly reduced section. The velocity may be obtained from Kutter's formula, and the values for n may be taken as 0.014 for lined tunnels and 0.028 for unlined. The safe velocity is from 10 to 15 feet per second.

While the circular cross-section would be most advantageous from the hydraulic point of view, tunnels are usually given a horseshoe shape (see Fig. 61) as this has been found to be the easiest to excavate. In order to permit quick construction, especially of long tunnels, one or more adits or openings are usually provided at certain intervals, so that the work can proceed from several headings at the same time.



Area of waterway	151 sq. ft.
Wetted perimeter	45 ft.
Hydraulic radius	3.3
Friction coefficient	.014
Grade	.002
C.	130

FIG. 61.—Typical Tunnel Section.

Pipe Lines. Pressure pipes must be used for conveying the water from the upper level at the forebay or dam to the wheels at the powerhouse. These may be constructed of steel, wood, and sometimes, although rarely, of concrete. The particular kind to use depends upon the head and the corresponding pressure.

Head. The total or gross head, as ordinarily understood, is the difference between the elevation of the water in the forebay and the tailrace. It must be distinguished from the net or effective head acting on the turbine, the difference between the two being equal to the head lost on account of friction in the penstock, etc.

The net or effective head at any point on the pipe line is equal to the sum of the pressure head at the point considered, plus the elevation head at the point above a datum plane plus the velocity head in the pipe. Thus

$$h=p+z+\frac{v^2}{2g},$$

where h = effective or net head in feet;

p = pressure head, this being equal to the pressure in pounds per square foot, at the point in consideration, divided by 62.4;

z = the elevation of the point above any arbitrary datum plane, in feet;

v = velocity at the point in feet per second.

The effective head at one point in a pipe will differ from that at another point, upstream or downstream from the first point, by an amount corresponding to the losses and, of course, to any work done or received between the two points, as when a machine, such as a turbine or pump, is placed in the pipe line. Considering only the losses, it follows that the effective head must decrease in the direction of the flow by an amount equal to the head lost. Therefore, although either the pressure, elevation, or velocity may increase in the direction of the flow, the sum of them must continually decrease, so that an increase in one of these items must always be accompanied by a corresponding decrease in one or both of the others.

In regard to the head to be used in computing the efficiency of an installation or a turbine, the turbine testing code of the turbine builders specifies the following:

"For the purpose of computing the plant efficiency, the total or gross head acting on the plant is to be used, and is to be taken as the difference in elevation between the equivalent still-water surface before the water has passed through the racks, to the equivalent still-water surface in the tailrace after discharge from the draft tube. When the water in the forebay in advance of the racks flows with sufficient velocity to make its velocity head an appreciable quantity, the actual elevation of the water surface shall be increased by the amount of this velocity head. The same process shall apply to the point of measurement in the tailrace; that is, the velocity head at the point of measurement in the tailrace shall be added to the actual elevation of the surface, the sum being considered the equivalent still-water elevation.

"In computing the efficiency of the turbine, the losses through racks, in the intake to the penstocks, and in the penstocks, shall not be charged against the turbine; nor shall the head necessary to set up the velocity required to discharge the water from the end of the draft tube be charged against the turbine.

"The net or effective head acting on turbines equipped with casings is to be taken as the difference between the elevation corresponding to the pressure in the penstock near the entrance to the turbine casing,

and the elevation of the tail water at the highest point attained by the discharge from the unit under test, the above difference being corrected by adding the velocity head in the penstock at the point of measurement and subtracting the residual velocity head at the end of the draft tube. The velocity head in the penstock shall be taken as the square of the mean velocity at the point of measurement, divided by $2g$; the mean velocity being equal to the quantity of water flowing in cubic feet per second, divided by the cross-sectional area of the penstock at the point of measurement in square feet. The residual velocity head at the end of the draft tube shall be taken as the square of the mean velocity at the end of the draft tube, divided by $2g$, the mean velocity being equal to the quantity flowing in cubic feet per second, divided by the final cross-sectional discharge area of the closed or submerged portion of the draft tube in square feet."

The loss of head is due to the loss in the entrance of the penstock, to the friction of the interior surface, to curvature, and to various other obstructions such as headgates, racks, and valves. In the case of impulse turbines, there is a further loss caused by the necessity of placing the wheel clear of tailwater so that after leaving the wheel the water drops freely through the vertical height between the wheel and the tailwater surface, and fails to utilize the head corresponding to this free fall. It is customary in computing the efficiency of impulse turbines to charge against the wheel only the net head with reference to the elevation of the center of the nozzle taken as datum.

Loss of Head in Entrance. This loss of head is probably due to internal friction of the particles of water against each other when they converge towards the contracted entrance. The loss depends on the shape of the intake, but for ordinary purposes it may be obtained from the formula

$$h_e = 0.5 \frac{v^2}{2g}.$$

Loss of Head in Friction. For determining the loss of friction in pipe lines there are two formulæ in very general use:

Chezy formula:

$$v = c\sqrt{rs} \text{ (for values of } c\text{, see page 101).}$$

Williams and Hazen formula:

$$v = 1.32 \quad cr^{0.63} \quad s^{0.54},$$

where v = velocity in feet per second;

r = hydraulic radius $=\frac{d}{4}$ for circular pipes, d being the diameter in feet;

s = hydraulic slope $=\frac{h_f}{l}$, where h_f represents the loss in head due to friction and l the length of pipe, both in feet;

c = friction coefficient.

In using the latter (Williams and Hazen) formula, the following values of the friction coefficient are recommended:

For cast-iron pipe........................ $c=120-110$
For riveted steel pipe...................... $c=105-100$
For wood-stave pipe....................... $c=130-120$

To facilitate the calculations when using their formula Williams and Hazen have published a book entitled "Hydraulic Tables," which contains a series of tables giving the values of friction losses for pipes of different materials and sizes, and also different degrees of roughness and for various velocities. This book is very useful, and may be obtained from John Wiley & Sons, Inc.

Merriman, in his "Treatise on Hydraulics," states the following in regard to the friction loss:

1. The loss of head in friction is directly proportional to the length of the pipe.
2. It is inversely proportional to the diameter of the pipe.
3. It increases nearly as the square of the velocity.
4. It is independent of the pressure of the water.
5. It increases with the roughness of the interior surface.

Thus,

$$h_f=f\times\frac{l}{d}\times\frac{v^2}{2g}.$$

The friction factor, f, depends upon the degree of roughness of the surface, the values given in Table XXXI being applicable to clean cast-iron or wrought-iron pipes.

Table XXXII [1] gives the loss in head in each 100 feet of riveted steel pipe for diameters from 2 to 12 feet and for velocities up to 12 feet per second.

[1] S. Morgan Smith Co.'s Bulletin, No. 104.

TABLE XXXI

Friction Factors for Clean Iron Pipes

Diameter in Feet.	Velocity in Feet per Second.						
	1	2	3	4	6	10	15
0.05	0.047	0.041	0.037	0.034	0.031	0.029	0.028
0.1	0.038	0.032	0.030	0.028	0.026	0.024	0.023
0.25	0.032	0.028	0.026	0.025	0.024	0.022	0.021
0.5	0.028	0.026	0.025	0.023	0.022	0.020	0.019
0.75	0.026	0.025	0.024	0.022	0.021	0.019	0.018
1.0	0.025	0.024	0.023	0.022	0.020	0.018	0.017
1.25	0.024	0.023	0.022	0.021	0.019	0.017	0.016
1.5	0.023	0.022	0.021	0.020	0.018	0.016	0.015
1.75	0.022	0.021	0.020	0.018	0.017	0.015	0.014
2.0	0.021	0.020	0.019	0.017	0.016	0.014	0.013
2.5	0.020	0.019	0.018	0.016	0.015	0.013	0.012
3.0	0.019	0.018	0.017	0.015	0.014	0.013	0.012
3.5	0.018	0.017	0.016	0.014	0.013	0.012	
4.0	0.017	0.016	0.015	0.013	0.012	0.011	
5.0	0.016	0.015	0.014	0.013	0.012		
6.0	0.015	0.014	0.013	0.012	0.011		

Loss of Head in Bends. This may be obtained from the formula:

$$h_b = f_1 \times \frac{b}{180} \times \frac{v^2}{2g},$$

where f_1 = curve factor, and

b = angle of the bend in degrees.

This formula is taken from M. W. Kellogg Company's bulletin, "High Pressure Pipe Lines." The curve factor, f_1, is determined from the relation $\frac{R}{d}$, R being the radius of the bend and d the pipe diameter.

For $\frac{R}{d}=$	5	4	3	2	1	0.75	0.5
$f_1=$	0.13	0.13	0.14	0.15	0.3	0.6	2.0

Hydraulic Gradient. The hydraulic gradient is, strictly speaking, a line representing atmospheric pressure conditions, although it may also conveniently be used as a graphical representation of the internal pressures in a pipe line at any point. It may also be defined as the line, the vertical distance between which and the center of the pipe gives the pressure heads at the respective points. For example, referring to

Fig. 62, the hydraulic gradient or grade line is a line through the points to which the water levels would rise if piezometer tubes were inserted along the pipe, as shown. The line will be approximately straight when the head is lost uniformly along the pipe, that is, if the size and surface of the entire length of pipe is the same.

The grade line should be drawn from a point A near the upper water-level, the distance AB being equal to the velocity head plus the entrance head, to a point at the end of the pipe. For a pipe discharging

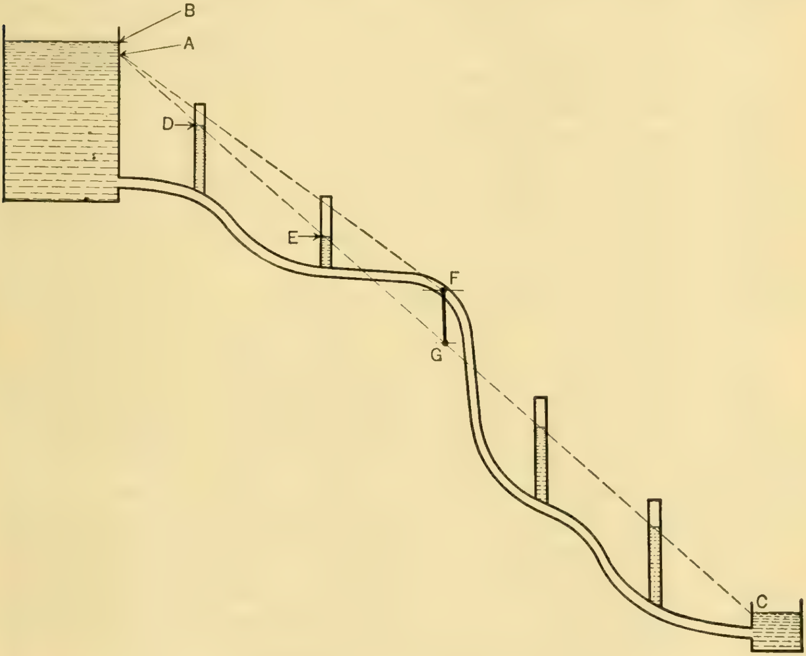


Fig. 62.—Hydraulic Gradient.

freely in the air, this would be the center of its outlet; but for a pipe with submerged discharge it would be the lower water level instead of the point of discharge.

The slope or drop in elevation along the pipe corresponds to the friction loss. For example, the vertical distance between D and E would be equal to the head lost on account of friction between these two points.

If the pipe is laid so that it rises above the hydraulic gradient AC, as at F, the pressure in the pipe at this point will be less than that of the atmosphere by a head corresponding to FG; thus it will be negative. If no air could enter the pipe it would act as a siphon, and the flow

would continue as usual, provided the distance *FG* did not exceed about 25 feet, the theoretical limit of vacuum being 34 feet.

However, air is always present in the water and will collect at the summit near *F*, with the result that the pressure will approach atmospheric. In this case the gradient would shift to *AF* and the discharge would only be that due to the vertical head between *B* and *F* instead of between *B* and *C*. The remainder of the pipe from *F* to *C* would merely act as a channel to deliver the flow.

From the above it is evident that the pipe line should be laid well below the hydraulic gradient. Much trouble may be avoided if, at the outset, a profile of the proposed route is prepared and the hydraulic gradient carefully calculated and drawn in.

Size of Pipe Line: In determining the size of a pipe line or penstock, the first thing to consider is the number of pipes and necessarily also the amount of water which each must be able to carry. As to the number, this should preferably be equal to the turbine units, as this secures a greater flexibility in the operation of the plant. It further does away with the large Y-distributing joints at the bottom of the penstocks, as well as with large-sized gate valves and heavy plate thicknesses.

In determining the most economical pipe-line installation for a hydro-electric plant, several factors in addition to the primary consideration of the grade or route must be studied. In general, these must have direct relation to the earning capacity with respect to the first cost. Usually, the pipe-line investment represents one of the principal items of the initial cost of the generating station. Especially is this apparent in connection with those installations where the pipe line is long and subject to high pressure. Because of its relatively high initial cost and consequent interest charge, a careful consideration of the pipe line must be made; otherwise, an injudicious monetary expenditure may result.

It is obvious that, for a given water quantity, the size of the pipe is determined by the velocity at which the water is allowed to run. This is the difficult point to settle; the velocity varies from 6 to 12 feet per second, the average probably being around 9 feet. A high velocity entails a considerable friction loss, while a low velocity necessitates a larger pipe and thus increases the cost of construction. For a low-head development a rather low velocity should be used, because the loss of head will then form a much larger percentage of the total head than where a high head is available. In high-head pipe lines of some length it is, of course, also more economical to use smaller diameter and larger velocity at the bottom, where the pressure is higher and thicker pipe is required.

Consideration must also be given to the load factor at which the turbine is running, i.e., the average amount of water which the pipe line is to carry. Some plants require that the turbines be run continuously at full gate opening, while in other instances they may operate normally at half gate, only opening up occasionally to full gate to take care of momentary peak loads. In such a case the friction loss should naturally be based on the water conveyed when the wheels are operating at half gate opening.

Theoretically, therefore, the economical diameter of a pipe line for a water-power development should be such that any increase in the diameter of the pipe would cost more than the value of the power which could be obtained from the decrease in loss of head due to friction from such increase in diameter. Or, stated in other words; the size of pipe should be such that the value of the power annually lost in friction plus the annual interest, profit and depreciation charges on the pipe line should be a minimum. For a steel pipe this leads to the following formula:[1]

$$d=\sqrt[6]{\frac{320\times Y\times X^2\times q^3\times e}{\pi^3\times t\times m\times i\times c^2}},$$

where d = economic diameter in feet for thickness t;

Y = weight of water in pounds per cubic foot = 62.4;

t = thickness of pipe in feet;

m = weight of material in pipe line in pounds per cubic foot = 490;

q = average flow of water through pipe during twenty-four hours, expressed in cubic feet per second;

e = sale value of 1 foot-pound per second for one year, measured in water before delivery to turbine;

i = annual interest, profit and depreciation charge on 1 pound of material in pipe line in place, expressed as a ratio. This value should be multiplied by whatever factor is necessary to make allowance for excess of actual weight of pipe line over theoretical weight due to lap, rivets, etc.;

c = friction coefficient. (See page 111.)

The factor X for a 50 per cent load factor will generally vary from 1.3 to 1.5. It may be figured from the formula:

$$X=\sqrt{\frac{\text{Average of the cubes of load curve ordinates}}{\text{Cube of the average of load curve ordinates}}}.$$

This means that the load curve may be divided into as many sections as desired for accuracy, and the mean ordinate of each section used in the formula.

[1] By courtesy of J. G. White & Co.

TABLE XXXII

Loss in Head in Each 100 Feet Length of Pipe at Different Velocities

Vel. in Feet Per Second.	Head Required to Produce Vel.	Head Required to Overcome Loss at Ent. of Pipe.	Friction Head in Feet for Pipes 100 Feet Long from 2 to 6 Feet Diameter Inclusive with Cubic Feet Discharge per Minute under Velocities from 1 to 12 Feet Inclusive per Second.									
			2′ Diam.		3′ Diam.		4′ Diam.		5′ Diam.		6′ Diam.	
			Friction Head.	Cubic Feet.	Friction Head.	Cubic Feet.	Friction Head.	Cubic Feet.	Friction Head.	Cubic Feet.	Friction Head.	Cubic Feet.
1.0	.01552	.00776	.024	188	.015	424	....	754	....	1,178	...	1,696
1.2	.02236	.01118	.033	226	.022	509	.016	905	.013	1,414	.011	2,036
1.4	.03043	.01521	.043	264	.029	594	.021	1056	.017	1,649	.014	2,375
1.6	.03975	.01987	.055	302	.036	679	.027	1206	.022	1,885	.018	2,714
1.8	.05031	.02515	.068	339	.045	763	.034	1357	.027	2,120	.022	3,054
2.0	.06211	.03105	.082	377	.054	848	.041	1508	.032	2,356	.027	3,393
2.2	.07515	.03787	.097	415	.064	933	.048	1659	.039	2,592	.032	3,732
2.4	.08944	.04472	.113	452	.075	1018	.057	1810	.045	2,827	.037	4,071
2.6	.10496	.05248	.131	490	.087	1103	.065	1960	.052	3,063	.043	4,411
2.8	.12173	.06086	.150	528	.099	1188	.075	2111	.060	3,299	.049	4,750
3.0	.13975	.06987	.169	565	.112	1272	.084	2262	.067	3,534	.056	5,089
3.2	.159	.0795	.190	603	.126	1357	.095	2413	.076	3,770	.063	5,429
3.4	.1795	.8975	.212	641	.141	1442	.106	2563	.085	4,006	.070	5,768
3.6	.20124	.10062	.235	679	.156	1527	.117	2714	.094	4,241	.078	6,107
3.8	.22422	.11211	.260	716	.173	1612	.130	2865	.104	4,477	.086	6,446
4.0	.24844	.12422	.285	754	.189	1697	.142	3016	.114	4,712	.094	6,786
4.2	.27391	.13695	.311	791	.207	1781	.155	3167	.124	4,948	.103	7,125
4.4	.30062	.15031	.339	829	.226	1866	.169	3317	.135	5,184	.112	7,464
4.6	.32888	.16444	.368	867	.245	1951	.184	3468	.147	5,419	.122	7,804
4.8	.35776	.17888	.397	905	.264	2036	.198	3619	.159	5,655	.132	8,143
5.0	.38819	.19409	.428	942	.285	2121	.214	3770	.171	5,891	.142	8,482
5.2	.41987	.20993	.46	980	.306	2205	.230	3921	.184	6,126	.153	8,821
5.4	.45279	.22639	.493	1018	.328	2290	.246	4071	.197	6,362	.164	9,161
5.6	.48695	.24347	.527	1056	.351	2375	.263	4222	.210	6,597	.175	9,500
5.8	.52235	.26117	.654	1093	.374	2460	.281	4373	.224	6,833	.187	9,839
6.0	.559	.279	.598	1131	.398	2545	.299	4524	.239	7,069	.199	10,179
6.2	.59689	.29844	.635	1169	.423	2630	.317	4675	.254	7,304	.211	10,518
6.4	.63602	.31801	.673	1206	.448	2714	.336	4825	.269	7,540	.224	10,857
6 6	.67639	.33819	.712	1244	.474	2799	.356	4976	.285	7,775	.237	11,197
6.8	.71801	.35900	.753	1282	.501	2884	.376	5127	.301	8,011	.250	11,536
7.0	.76086	.38043	.794	1319	.529	2969	.397	5278	.317	8,247	.264	11,875
7.2	.80496	.40248	.836	1357	.557	3054	.418	5429	.334	8,482	.278	12,214
7.4	.85031	.42515	.880	1395	.586	3138	.440	5579	.352	8,718	.293	12,554
7.6	.89689	.44844	.924	1433	.616	3223	.462	5830	.369	8,954	.307	12,893
7.8	.94472	.47236	.970	1470	.646	3308	.485	5881	.388	9,189	.323	13,232
8.0	.99378	.49389	1.01	1508	.677	3393	.508	6032	.406	9,425	.338	13,572
8.2	1.04409	.52204	1.06	1546	.709	3478	.532	6182	.425	9,660	.354	13,911
8.4	1.09565	.54782	1.11	1583	.741	3563	.556	6333	.445	9,896	.370	14,250
8.6	1.14844	.57422	1.16	1621	.774	3647	.581	6484	.465	10,132	.387	14,589
8.8	1.20248	.60124	1.21	1659	.808	3732	.606	6635	.485	10,367	.404	14,929
9.0	1.25776	.62888	1.26	1696	.843	3817	.632	6786	.506	10,603	421	15,268
9.2	1.31428	.65714	1.31	1734	.878	3902	.658	6936	.527	10,839	.439	15,607
9.4	1.37254	.68602	1.37	1772	.913	3987	.685	7087	.548	11,074	.456	15,947
9.6	1.43105	.71552	1.42	1809	.950	4072	.713	7238	.570	11,310	.475	16,286
9.8	1.49130	.74565	1.48	1847	.987	4156	.741	7389	.592	11,545	.493	16,625
10.0	1.55279	.77639	1.53	1885	1.02	4241	.769	7540	.615	11,781	.512	16,964
10.2	1.61552	.80776	1.59	1923	1.06	4326	.798	7690	.638	12,017	.532	17,304
10.4	1.6795	.83975	1.65	1960	1.10	4411	.827	7841	.662	12,252	.551	17,643
10.6	1.74472	.87236	1.71	1998	1.14	4496	.857	7992	.686	12,488	.571	17,982
10.8	1.81118	.90559	1.77	2036	1.18	4580	.888	8143	.710	12,723	.592	18,322
11.0	1.87888	.93944	1.83	2073	1.22	4665	.919	8294	.735	12,959	.612	18,661
11.2	1.94782	.97391	1.90	2111	1.26	4750	.950	8444	.760	13,195	.633	19,000
11.4	2.01801	1.009	1.96	2149	1.31	4835	.982	8595	.786	13,430	.655	19,339
11.6	2.08944	1.04472	2.02	2187	1.35	4920	1.01	8746	.811	13,666	.676	19,679
11.8	2.16211	1.08105	2.09	2224	1.39	5005	1.04	8897	.838	13,902	.698	20,018
12.0	2.23602	1.11801	2.16	2262	1.44	5089	1.08	9048	.865	14,137	.720	20,357

TABLE XXXII.—*Continued*

Vel. in Feet Per Second.	Head Required to Produce Vel.	Head Required to Overcome Loss at Ent. of Pipe.	Friction Head in Feet for Pipes 100 Feet Long from 7 to 12 Feet Diameter Inclusive with Cubic Feet Discharge per Minute under Velocities from 1 to 12 Feet Inclusive per Second.									
			7′ Diam.		8′ Diam.		9′ Diam.		10′ Diam.		12′ Diam.	
			Friction Head.	Cubic Feet.	Friction Head.	Cubic Feet.	Friction Head.	Cubic Feet.	Friction Head.	Cubic Feet.	Friction Head.	Cubic Feet.
1.0	.01552	.00776	....	2,309	....	3,016	....	3,817	....	4,712	....	6,786
1.2	.02236	.01118	....	2,771	....	3,619	....	4,580	....	5,655	....	8,143
1.4	.03043	.01521	.012	3,233	....	4,222	....	5,344	....	6,597	....	9,500
1.6	.03975	.01987	.015	3,695	.013	4,825	.012	6,107	.011	7,540	....	10,858
1.8	.05031	.02515	.019	4,156	.017	5,429	.015	6,871	.013	8,482	.011	12,215
2.0	.06211	.03105	.023	4,618	.020	6,032	.018	7,634	.016	9,425	.013	13,572
2.2	.07515	.03757	.027	5,080	.024	6,635	.021	8,397	.019	10,367	.016	14,929
2.4	.08944	.04472	.032	5,542	.028	7,238	.025	9,161	.022	11,310	.018	16,286
2.6	.10496	.05248	.037	6,004	.032	7,841	.029	9,924	.026	12,252	.021	17,644
2.8	.12173	.06086	.042	6,465	.039	8,445	.033	10,688	.030	13,195	.024	19,001
3.0	.13975	.06987	.048	6,927	.042	9,048	.037	11,451	.033	14,137	.028	20,358
3.2	.159	.0795	.054	7,389	.047	9,651	.042	12,214	.038	15,080	.031	21,715
3.4	.1795	.08975	.060	7,851	.053	10,254	.047	12,978	.042	16,022	.035	23,072
3.6	.20124	.10062	.067	8,313	.058	10,857	.052	13,741	.047	16,965	.039	24,430
3.8	.22422	.11211	.074	8,775	.065	11,460	.057	14,505	.052	17,907	.043	25,787
4.0	.24844	.12422	.081	9,236	.071	12,064	.063	15,268	.057	18,850	.047	27,144
4.2	.27391	.13695	.088	9,698	.077	12,667	.069	16,031	.062	19,792	.051	28,501
4.4	.30062	.15031	.097	10,160	.084	13,270	.075	16,795	.067	20,735	.056	29,858
4.6	.32888	.16444	.105	10,622	.092	13,873	.081	17,558	.073	21,677	.061	21,216
4.8	.35776	.17888	.113	11,084	.099	14,476	.088	18,322	.079	22,620	.066	32,573
5.0	.38819	.19409	.122	11,546	.107	15,080	.095	19,085	.085	23,562	.071	33,930
5.2	.41987	.20993	.131	12,007	.115	15,683	.102	19,849	.092	24,504	.076	35,287
5.4	.45279	.22639	.140	12,469	.123	16,286	.109	20,612	.098	25,447	.082	36,664
5.6	.48095	.24347	.150	12,931	.131	16,889	.117	21,375	.105	26,389	.087	38,002
5.8	.52235	.26117	.160	13,393	.140	17,492	.124	22,139	.112	27,332	.093	39,359
6.0	.559	.2795	.170	13,855	.149	18,095	.132	22,902	.119	28,274	.099	40,716
6.2	.59689	.29844	.181	14,316	.158	18,699	.141	23,666	.127	29,217	.105	42,073
6.4	.63602	.31801	.192	14,778	.168	19,302	.149	24,429	.134	30,159	.112	43,430
6.6	.67639	.33819	.203	15,240	.178	19,905	.158	25,192	.142	31,102	.118	44,788
6.8	.71801	.3590	.215	15,702	.188	20,508	.167	25,956	.150	32,044	.125	46,145
7.0	.76086	.3843	.226	16,164	.198	21,111	.176	26,719	.158	32,987	.132	47,502
7.2	.80496	.40248	.238	16,626	.209	21,714	.185	27,483	.167	33,929	.139	48,859
7.4	.85031	.42515	.251	17,087	.220	22,318	.195	28,246	.176	34,872	.146	50,216
7.6	.89689	.44844	.264	17,549	.231	22,921	.205	29,009	.184	35,814	.154	51,574
7.8	.94472	.47236	.277	18,011	.242	23,524	.215	29,773	.194	36,757	.161	52,931
8.0	.99378	.49689	.290	18,473	.254	24,127	.225	30,536	.203	37,699	.169	54,288
8.2	1.04409	.52204	.303	18,935	.266	24,730	.236	31,300	.212	38,642	.177	55,645
8.4	1.09565	.54782	.317	19,396	.278	25,334	.247	32,063	.222	39,584	.185	57,002
8.6	1.14844	.57422	.332	19,858	.290	25,937	.258	32,826	.232	40,527	.193	58,360
8.8	1.20248	.60124	.346	20,320	.303	26,540	.269	33,590	.242	41,469	.202	59,717
9.0	1.25776	.62888	.361	20,782	.316	27,143	.281	34,353	.253	42,412	.210	61,074
9.2	1.31428	.65714	.376	21,244	.329	27,746	.292	35,117	.263	43,354	.219	62,431
9.4	1.37204	.68602	.391	21,706	.342	28,349	.304	35,880	.274	44,297	.228	63,788
9.6	1.43105	.71552	.407	22,167	.356	28,953	.316	36,643	.285	45,239	.237	65,146
9.8	1.49130	.74565	.423	22,629	.370	29,556	.329	37,407	.296	46,182	.247	66,503
10.0	1.55279	.77639	.439	23,091	.384	30,159	.341	38,170	.307	47,124	.256	67,860
10.2	1.61552	.80776	.456	23,553	.399	30,762	.354	38,943	.319	48,066	.266	69,217
10.4	1.6795	.83975	.472	24,015	.413	31,365	.367	39,697	.331	49,009	.275	70,574
10.6	1.74472	.87236	.490	24,476	.428	31,969	.381	40,460	.343	49,951	.285	71,932
10.8	1.81118	.90559	.507	24,938	.444	32,575	.394	41,224	.355	50,894	.296	73,289
11.0	1.87888	.93944	.525	25,400	.459	33,175	.408	41,987	.367	51,836	.306	74,646
11.2	1.94782	.97391	.543	25,862	.475	33,778	.422	42,751	.380	52,779	.316	76,003
11.4	2.01801	1.009	.561	26,324	.491	34,381	.436	43,514	.393	53,721	.327	77,360
11.6	2.08944	1.04472	.579	26,786	.507	34,984	.450	44,277	.405	54,664	.338	78,718
11.8	2.16211	1.08105	.598	27,247	.524	35,588	.565	45,041	.419	55,606	.349	80,075
12.0	2.23602	1.11801	.617	27,709	.540	36,191	.480	45,804	.432	56,459	.360	81,432

Having determined the economic diameter for a given thickness, that for any other thickness, all other conditions remaining the same, varies inversely as the sixth root of the thickness.[1]

Speed regulation must also be considered in determining the size of a pipe line, and this point is probably of more importance than the consideration of economy. Load changes on the turbine cause the governor to open or close the turbine gates rapidly, thus causing pressure changes in the penstock. These pressure changes are due to the acceleration or deceleration of the water column in the pipe line, and the magnitude of the same depends upon both the length of the penstock and the change of velocity in the same.

The pressure changes always act in opposition to the action of the governor; thus, when a load suddenly goes off the generator and the turbine gates close, there is an increase in pressure in the penstock which tends to develop more horse-power, and vice versa. When a load comes on the generator and the turbine gates open, there is a drop in pressure in the penstock, tending to decrease the output of the turbine. As the length of the penstock for any particular installation is fixed, it is necessary to limit the changes in velocity in the penstock, in order to give reasonably good speed regulations.

Excessive rises in pressure may be eliminated by the use of pressure regulators or surge tanks. After the size of the penstock has been tentatively settled as most suitable for economical considerations, it must then be investigated for speed regulation. This investigation may indicate the necessity of using a larger pipe than is consistent with the highest economy. (See also Surge Tanks and Pressure Regulators.)

Steel Pipe. These may be made of rolled steel plates, riveted together, Fig. 63, or lap-welded, the latter being used for very high heads where the pressure is excessive and where the use of the riveted construction would greatly increase the thickness of the plate. In figuring the thickness of the plate, it is necessary to consider not only the pressure due to the net head but also the additional pressure caused by the water hammer.

There are several formulae for the calculation of the strength of pipe lines; manufacturers' bulletins contain many valuable data for such purposes and should be freely consulted.

A general formula for calculating the strength of riveted steel pipe is

$$t = \frac{Pdf}{2Te},$$

[1] See also "Economical Penstock Size," by M. Warren, A.S.C.E., Dec. 2, 1914.

Where t = thickness of plate in inches;

P = pressure in pounds per square inch;

d = diameter of pipe in inches;

f = factor of safety, based on the ultimate tensile strength; (4 is a factor generally used in this country);

T = tensile strength = 50,000 for mild steel;
= 60,000 for wrought iron;

e = efficiency of riveted joint = approximately 0.60 for single rivets and 0.70 for double rivets.

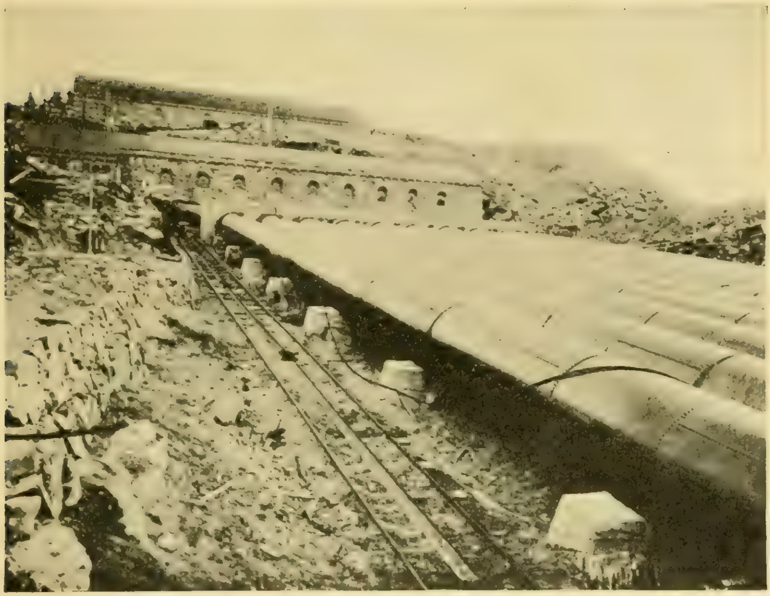


FIG. 63.—Ten Five-foot Riveted Steel Penstocks.

Table XXXIII[1] gives the safe working heads and weights of riveted steel pipes.

It would seem advisable, in proportioning the thickness of penstocks, to provide, in addition to the thickness computed by the above formula, an allowance for corrosion; that is, the addition of a constant term to the thickness, say $\frac{1}{8}$ inch or whatever is considered advisable under the conditions of installation.

Another point which must be given very careful consideration in connection with the calculation of pipe-line sizes and thicknesses is their safety from collapsing, due to sudden drop in pressure. The

[1] Pelton Water Wheel Company.

TABLE XXXIII

Safe Working Heads and Weights of Riveted Steel Pipes

Heavy-face figures = weight per foot.
Light-face figures = safe head in feet.
Safety factor = 4.
Tensile strength = 55,000 pounds per square inch.
Efficiency of riveted joint = 70 per cent.

Diameter. In.	Plate Thickness											Diameter. In.
	No. 12	No. 10	No. 8	3/16″	1/4″	5/16″	3/8″	7/16″	1/2″	9/16″	5/8″	
10	**15.2**	**18.8**	**23.3**									**10**
	483	592	730									
12	**17.9**	**22.2**	**26.5**	**32.0**	**44.6**							**12**
	401	493	607	690	921							
14	**20.6**	**25.8**	**31.6**	**36.7**	**49.4**							**14**
	343	423	511	592	790							
16	**23.3**	**28.9**	**35.8**	**41.4**	**56.0**							**16**
	300	368	456	518	692							
18	**26.0**	**32.2**	**40.0**	**46.1**	**62.2**	**78.3**						**18**
	268	329	405	460	615	768						
20	**28.6**	**35.3**	**44.0**	**50.6**	**68.5**	**86.4**	**104.3**					**20**
	240	296	365	414	553	691	830					
22	**31.4**	**38.9**	**48.1**	**55.6**	**74.9**	**94.9**	**114.9**	**135.8**	**154.9**			**22**
	218	269	331	377	503	630	755	880	1006			
24	**34.2**	**42.2**	**52.3**	**60.3**	**81.2**	**102.9**	**124.3**	**146.4**	**168.6**			**24**
	201	247	303	346	461	576	692	807	922			
26	**36.8**	**45.3**	**56.4**	**64.9**	**87.5**	**110.7**	**134.0**	**160.0**	**185.9**			**26**
	184	228	280	320	426	534	640	748	856			
28	**39.6**	**48.7**	**60.4**	**69.8**	**93.9**	**119.0**	**143.7**	**170.8**	**197.8**	**224.0**	**250.0**	**28**
	172	211	260	296	395	494	593	692	790	873	988	
30	**42.3**	**52.1**	**64.6**	**74.6**	**99.1**	**126.8**	**153.4**	**182.4**	**211.3**	**239.4**	**266.8**	**30**
	161	197	243	276	368	461	553	645	738	830	922	
32	**45.0**	**55.5**	**68.7**	**79.2**	**106.4**	**134.7**	**162.9**	**191.2**	**219.7**	**251.3**	**283.0**	**32**
	150	184	228	259	346	432	519	605	692	777	865	
34	**47.8**	**58.8**	**72.9**	**83.9**	**112.9**	**142.7**	**172.5**	**204.2**	**236.0**	**267.8**	**299.1**	**34**
	141	173	214	243	325	406	488	569	651	731	813	
36	**50.5**	**62.0**	**76.9**	**88.8**	**118.1**	**149.5**	**181.0**	**213.0**	**247.2**	**281.0**	**314.8**	**36**
	133	164	202	230	307	384	461	538	615	692	768	
38		**65.8**	**81.0**	**92.3**	**125.1**	**157.0**	**189.0**	**224.0**	**259.0**	**293.8**	**328.6**	**38**
		155	191	217	289	362	435	507	578	652	725	
40		**68.7**	**85.1**	**98.1**	**131.8**	**167.0**	**199.1**	**235.9**	**272.9**	**310.2**	**347.9**	**40**
		148	182	206	276	346	414	484	553	622	691	
42		**72.0**	**89.3**	**102.8**	**138.0**	**173.1**	**208.1**	**246.0**	**283.7**	**324.0**	**364.1**	**42**
		140	173	197	263	329	396	461	517	593	658	
44			**93.4**	**107.4**	**144.2**	**180.9**	**217.3**	**257.3**	**297.8**	**339.2**	**380.0**	**44**
			164	188	250	314	377	439	502	565	628	
46			**97.5**	**112.0**	**150.3**	**188.3**	**226.5**	**268.8**	**310.8**	**353.6**	**396.4**	**46**
			158	181	239	300	360	420	480	541	601	
48			**101.6**	**117.2**	**158.1**	**196.4**	**235.1**	**279.2**	**323.5**	**366.5**	**410.0**	**49**
			151	173	230	288	346	403	461	519	576	
50				**121.7**	**162.5**	**204.2**	**246.2**	**290.1**	**334.5**	**381.6**	**428.5**	**50**
				165	220	276	331	386	442	497	552	
52				**126.6**	**169.7**	**212.6**	**255.6**	**302.8**	**350.8**	**398.2**	**445.2**	**52**
				159	212	265	318	371	424	477	531	
54				**131.3**	**176.1**	**220.3**	**265.1**	**313.5**	**362.0**	**412.2**	**462.0**	**54**
				153	205	256	307	358	410	461	512	
56				**136.1**	**182.4**	**228 6**	**275.0**	**326.1**	**377.3**	**426.2**	**477.6**	**56**
				149	198	249	298	348	398	447	498	
	No. 12	No. 10	No. 8	3/16″	1/4″	5/16″	3/8″	7/16″	1/2″	9/16″	5/8″	

following formula gives the maximum difference between the external and the internal pressures which a circular steel pipe can withstand:

$$p=50,200,000\left(\frac{t}{d}\right)^3,$$

where p = pressure difference in pounds per square inch;
t = thickness of plate in inches;
d = diameter of pipe in inches.

A study must be made of the entire penstock from the headgates to the turbine casing, and the exact drop in pressure calculated at each section under the most severe conditions. Such conditions might occur when a turbine unit is running light, and a short circuit occurs on the generator, in which case the turbine gates open wide very quickly, and there is a tendency to accelerate the water in the various sections of the pipe line.

In a long penstock, the water column below a certain section may have sufficient head to be accelerated more rapidly than the water column above. This may cause a break in the water column at the section in question, and a considerable vacuum, which is very likely to collapse the penstock. To prevent this, air vents (see page 147) may be provided at the points along the pipe line where dangers are expected, as whenever the pipe greatly increases its slope or rate of fall. The amount of air which must be admitted to keep the pressure from going below a certain given value must be such as will, at the given pressure, replace the water which has run away from the section.

On account of the uncertainty of the calculation of the collapsing strength of a riveted steel pipe, and in order to provide a margin of safety, it would seem to be the best practice to provide against any excess of external over internal pressure at any point in the pipe line, rather than attempt to compute the collapsing pressure. The critical points subject to a deficient internal pressure can best be located by drawing a hydraulic gradient under conditions of accelerated or retarded flow in the pipe line.

For a more complete treatise on this important subject, the reader is referred to an article by Enger and Seely, in *Engineering Record,* for May 23, 1914.

Expansion joints are not usually employed in this country; and if the pipe is carefully laid and buried or kept with water flowing at all times, they are not required except in special cases. Whether the pipes are buried or not, they should be carried on concrete piers. Heavy anchorage blocks should be inserted at all vertical and horizontal

bends; and where there are considerable temperature variations, expansion joints should be provided to take care of the expansion and contraction of the pipe. While the stress may be well within the elastic limit of the pipe material, and would have little influence on the pipe itself, the thrust caused by the expansion may throw a very high stress on the anchorage blocks. By providing expansion joints a material saving can often be effected in the cost of anchorage blocks and piers, especially where their construction involves difficulties owing to the steepness of the grade and lack of handling facilities. A detail design of an expansion joint is shown in Fig. 64; and in Figs. 65 and 66 are shown a typical penstock installation and details of supporting and anchoring piers.

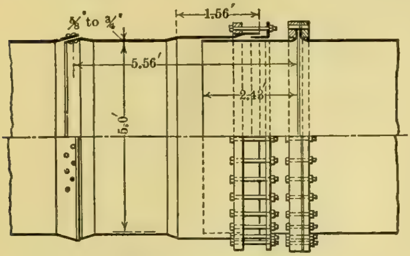


Fig. 64.—Pipe Line Expansion Joint.

Fig. 65.—Large Hydro-Electric Power Station at Rjukan, Norway, Showing Ten Five-foot Penstocks and Method of Anchoring Same.

It is often essential to know the amount of water that must pass through the penstock, in order to prevent freezing, as for example

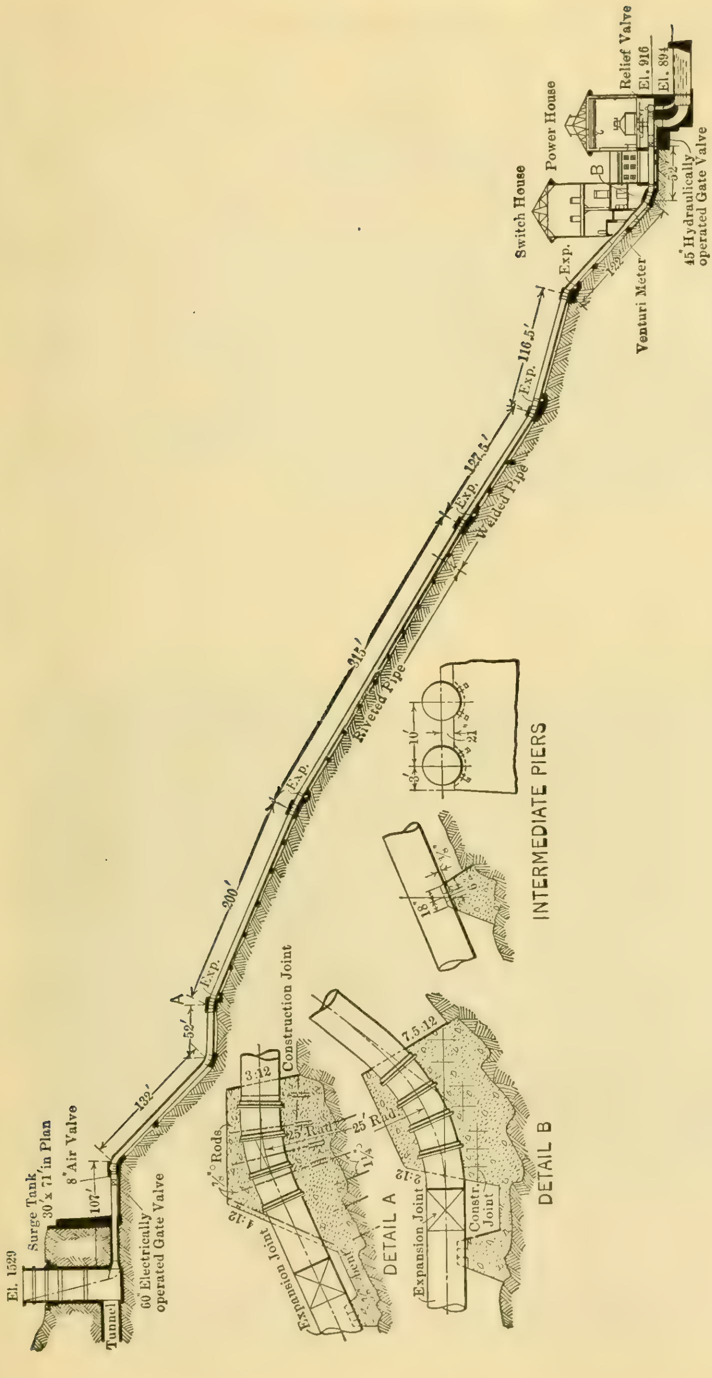


FIG. 66.—Penstock Showing Location of Expansion Joints and Method of Anchoring. Georgia Railway, Light and Power Company.

during the shut-down of a unit. This may be obtained from the following formula by Boucher:

$$Q=\frac{T_a-\frac{T_w}{2}}{20\quad T_w}\times S,$$

where Q = Water discharge in cubic meters per hour;
T_a = Lowest air temperature in degrees Centigrade; without negative sign;
T_w = Water temperature in degrees Centigrade (may be taken as 1° C.);
S = Exposed surface of penstock in square meters.

Wood-stave Pipe.[1] This kind of pipe is extensively used in the West, where redwood or fir is cheap and plentiful. It is admirably adapted for heads up to about 200 feet and has been used for heads as high as 400 feet with small diameter pipes. For high-head developments it is often used for the upper sections. For heads above 200 feet, steel pipe is preferable, as the spacing of the bands for wood-stave pipe becomes so close that the cost of the pipe may equal or exceed that of steel.

Wood-stave pipe has a greater carrying capacity than steel pipe on account of the smooth surface of the planed wood. Its carrying capacity will not decrease greatly with age, as deposits will not adhere to the inside of the pipe to any great extent.

A wood-stave pipe should always be in use, so that the staves are thoroughly saturated. Under these conditions they will not decay and leakages will be prevented. Provisions are made, however, that the staves may readily be drawn firmly together by tightening the bands.

Continuous wood-stave pipe is constructed in place. It should preferably be located above ground and free from all contact with it, cradles being provided at certain intervals for the support (Figs. 67 and 68).

In erecting the pipe, the staves are assembled and put together to form a circle of the diameter of the pipe, and the bands put around the outside and tightened to hold the staves together. The end joints in the staves should be broken by a lap of not less than 1 foot, and they can be made tight by inserting a metal tongue or plate in the saw kerf cut in the ends of the staves. After the pipe is completed and before

[1] An excellent treatise on wood-stave pipe is found in Bulletins Nos. 155 and 376 U. S. Dept. of Agriculture.

the water is turned on, the bands should be tightened uniformly so as to give tension on all the bands. When the pipe is filled with water, the

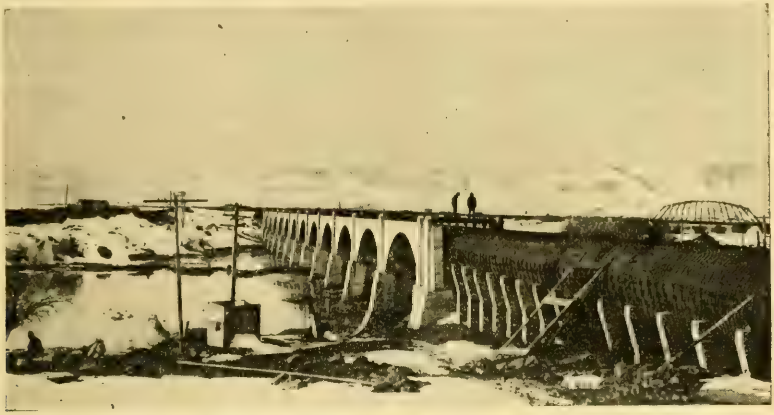


FIG. 67.—Wood-stave Pipe Showing Method of Installation in Difficult Territory.

staves swell sufficiently to bed the bands slightly into the wood and make the longitudinal joints water-tight.

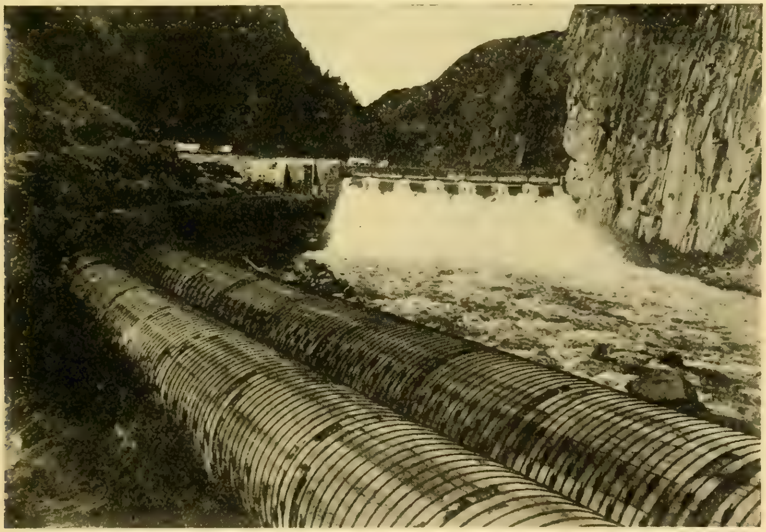


FIG. 68.—Montana Power Company. Dam and Wooden Penstocks for Madison No. 2 Plant.

The size of the bands and the spacing are naturally related, and when properly designed they should be strained to their safe resisting

value, and the bearing pressure on the stave must not be greater than the safe bearing value of the wood. It has been found from actual experience that the width of contact between the band and pipe is equal to about the radius of the band before the fibers of the wood are crushed beyond safety. The safe crushing stress for wood is generally taken as 650 pounds per square inch; putting the safe stress in the band equal to the safebearing pressure, we get

$$\pi r^2 s = (R+t)650r,$$

or

$$r = \frac{(R+t)650}{\pi s},$$

where r = radius of band in inches;
R = internal radius of pipe in inches;
t = thickness of stave in inches;
s = safe tensile strength of band. Taking the ultimate strength of steel as 60,000 pounds, and assuming a factor of safety of 4, the safe strength is 15,000 pounds per square inch.

The number, and thus the spacing, of the bands depends on the stresses due to the water pressure and to the swelling of the wood. The sum of these two stresses should be equal to the safe strength of the band. as determined by the previous formula.
Thus

$$\pi r^2 s = pdR + tdE,$$

and

$$d = \frac{\pi r^2 s}{pR + tE},$$

where d = spacing of bands in inches;
p = water pressure in pounds per square inch;
E = swelling force of wood per square inch. This is usually assumed to be approximately equal to 100.

For large-sized pipes and high pressures, the stress due to the swelling action is relatively small and may be neglected, in which case the equation can be written,

$$d = \frac{\pi r^2 s}{pR}.$$

The friction losses may be obtained from Hazen and Williams' formula on page 110, and the Table XXXIV[1] gives the discharge, velocity and loss of head per 100 feet for pipes of different diameters.

[1] As given by Washington Pipe and Foundry Company.

TABLE XXXIV

Flow of Water through Wood-stave Pipe

2 Feet Diameter.			3 Feet Diameter.			4 Feet Diameter.		
Discharge, Cu.ft. per Sec.	Velocity, Feet per Sec.	Loss of Head in Feet per 100 Feet of Pipe.	Discharge, Cu.ft. per Sec.	Velocity, Feet per Sec.	Loss of Head in Feet per 100 Feet of Pipe.	Discharge, Cu.ft. per Sec.	Velocity, Feet per Sec.	Loss of Head in Feet per 100 Feet of Pipe.
1.5	0.48	0.003	4	0.57	0.003	6	0.48	0.002
3.0	0.95	0.012	8	1.13	0.010	12	0.95	0.006
4.5	1.43	0.025	12	1.70	0.021	18	1.43	0.011
6.0	1.91	0.042	16	2.26	0.035	24	1.91	0.018
7.5	2.39	0.064	20	2.83	0.054	30	2.39	0.028
9.0	2.86	0.090	24	3.40	0.077	36	2.86	0.040
10.5	3.34	0.122	28	3.96	0.105	42	3.34	0.054
12.0	3.82	0.159	32	4.53	0.137	48	3.82	0.070
13.5	4.30	0.201	36	5.09	0.173	54	4.30	0.088
15.0	4.77	0.248	40	5.66	0.213	60	4.77	0.108
16.5	5.25	0.300	44	6.22	0.258	66	5.25	0.131
18.0	5.73	0.356	48	6.79	0.306	72	5.73	0.156
19.5	6.21	0.416	52	7.36	0.358	78	6.21	0.183
21.0	6.68	0.482	56	7.92	0.415	84	6.68	0.212
22.5	7.16	0.553	60	8.49	0.476	90	7.16	0.243
24.0	7.64	0.629	64	9.05	0.542	96	7.64	0.276
25.5	8.12	0.709	68	9.62	0.613	102	8.12	0.311
27.0	8.59	0.793	72	10.19	0.687	108	8.59	0.349
28.5	9.07	0.881	76	10.75	0.764	114	9.07	0.389
30.0	9.55	0.974	80	11.32	0.846	120	9.55	0.431
31.5	10.03	1.073	84	11.88	0.933	126	10.03	0.475
33.0	10.50	1.178	88	12.45	1.024	132	10.50	0.521
34.5	10.98	1.287	92	13.02	1.118	138	10.98	0.569
36.0	11.46	1.400	96	13.58	1.216	144	11.46	0.619
37.5	11.94	1.519	100	14.15	1.319	150	11.94	0.671
39.0	12.41	1.643	104	14.71	1.427	156	12.41	0.725
40.5	12.89	1.772	108	15.28	1.539	162	12.89	0.781
42.0	13.37	1.907	112	15.85	1.655	168	13.37	0.840
43.5	13.85	2.046	116	16.41	1.775	174	13.85	0.901
45.0	14.32	2.189	120	16.98	1.900	180	14.32	0.965

TABLE XXXIV—*Continued*

5 Feet Diameter.			6 Feet Diameter.			7 Feet Diameter.		
Discharge, Cu.ft. per Sec.	Velocity, Feet per Sec.	Loss of Head in Feet per 100 Feet of Pipe.	Discharge, Cu.ft. per Sec.	Velocity, Feet per Sec.	Loss of Head in Feet per 100 Feet of Pipe.	Discharge, Cu.ft. per Sec.	Velocity, Feet per Sec.	Loss of Head in Feet per 100 Feet of Pipe.
10	0.51	0.001	15	0.53	0.001	20	0.52	0.002
20	1.02	0.004	30	1.06	0.004	40	1.04	0.004
30	1.53	0.009	45	1.59	0.008	60	1.56	0.007
40	2.04	0.016	60	2.12	0.014	80	2.08	0.012
50	2.55	0.025	75	2.65	0.022	100	2.60	0.018
60	3.06	0.036	90	3.18	0.032	120	3.12	0.026
70	3.57	0.048	105	3.71	0.043	140	3.64	0.035
80	4.07	0.062	120	4.24	0.056	160	4.16	0.045
90	4.58	0.078	135	4.77	0.070	180	4.68	0.057
100	5.09	0.096	150	5.31	0.086	200	5.20	0.070
110	5.60	0.116	165	5.84	0.104	220	5.72	0.085
120	6.11	0.138	170	6.37	0.124	240	6.24	0.102
130	6.62	0.162	195	6.90	0.145	260	6.76	0.120
140	7.13	0.188	210	7.43	0.168	280	7.28	0.139
150	7.64	0.216	225	7.96	0.193	300	7.80	0.159
160	8.15	0.246	240	8.49	0.219	320	8.32	0.180
170	8.66	0.277	255	9.02	0.247	340	8.83	0.203
180	9.17	0.310	270	9.55	0.276	360	9.35	0.227
190	9.68	0.345	285	10.08	0.307	380	9.87	0.253
200	10.19	0.382	300	10.61	0.340	400	10.39	0.280
210	10.70	0.421	315	11.14	0.375	420	10.91	0.308
220	11.20	0.462	330	11.67	0.412	440	11.43	0.337
230	11.71	0.505	345	12.20	0.451	460	11.95	0.368
240	12.22	0.550	360	12.73	0.491	480	12.47	0.401
250	12.73	0.597	375	13.26	0.532	500	12.99	0.436
260	13.24	0.646	390	13.79	0.575	520	13.51	0.472
270	13.75	0.696	405	14.32	0.620	540	14.03	0.509
280	14.26	0.748	420	14.85	0.666	560	14.55	0.548
290	14.77	0.802	435	15.38	0.714	580	15.07	0.588
300	15.28	0.858	450	15.92	0.764	600	15.59	0.629

TABLE XXXIV—*Continued*

8 Feet Diameter.			9 Feet Diameter.			10 Feet Diameter.		
Discharge, Cu.ft. per Sec.	Velocity, Feet per Sec.	Loss of Head in Feet per 100 Feet of Pipe.	Discharge, Cu.ft. per Sec.	Velocity, Feet per Sec.	Loss of Head in Feet per 100 Feet of Pipe.	Discharge, Cu.ft. per Sec.	Velocity, Feet per Sec.	Loss of Head in Feet per 100 Feet of Pipe.
30	0.60	0.001	30	0.47	0.001	40	0.51	0.001
60	1.19	0.004	60	0.94	0.002	80	1.02	0.002
90	1.79	0.008	90	1.41	0.004	120	1.53	0.004
120	2.39	0.014	120	1.89	0.008	160	2.04	0.008
150	2.98	0.021	150	2.36	0.012	200	2.55	0.013
180	3.58	0.030	180	2.83	0.017	240	3.06	0.018
210	4.18	0.041	210	3.30	0.023	280	3.57	0.024
240	4.77	0.053	240	3.77	0.030	320	4.07	0.032
270	5.37	0.067	270	4.24	0.038	360	4.58	0.040
306	5.97	0.083	300	4.72	0.046	400	5.09	0.049
330	6.56	0.100	330	5.19	0.056	440	5.60	0.059
360	7.16	0.119	360	5.66	0.067	480	6.11	0.070
390	7.76	0.139	390	6.13	0.078	520	6.62	0.082
420	8.36	0.161	420	6.90	0.090	560	7.13	0.095
450	8.95	0.185	450	7.07	0.104	600	7.64	0.109
480	9.55	0.211	480	7.55	0.118	640	8.15	0.124
510	10.15	0.238	510	8.02	0.133	680	8.66	0.140
540	10.74	0.267	540	8.49	0.149	720	9.17	0.157
570	11.34	0.297	570	8.96	0.165	760	9.68	0.175
600	11.94	0.329	600	9.43	0.183	800	10.19	0.194
630	12.53	0.362	630	9.90	0.202	840	10.70	0.214
660	13.13	0.397	660	10.38	0.222	880	11.20	0.235
690	13.73	0.434	690	10.85	0.243	920	11.71	0.257
720	14.32	0.437	726	11.32	0.264	960	12.22	0.280
750	14.92	0.514	750	11.79	0.286	1000	12.73	0.303
780	15.52	0.556	780	12.26	0.309	1040	13.24	0.328
810	16.11	0.599	810	12.73	0.333	1080	13.75	0.354
840	16.71	0.644	840	13.20	0.358	1120	14.20	0.381
870	17.31	0.690	870	13.68	0.385	1160	14.77	0.408
900	17.90	0.738	900	14.15	0.413	1200	15.28	0.437

The following formula, given in Bulletin No. 376 of the United States Department of Agriculture, is said to be based on an extended

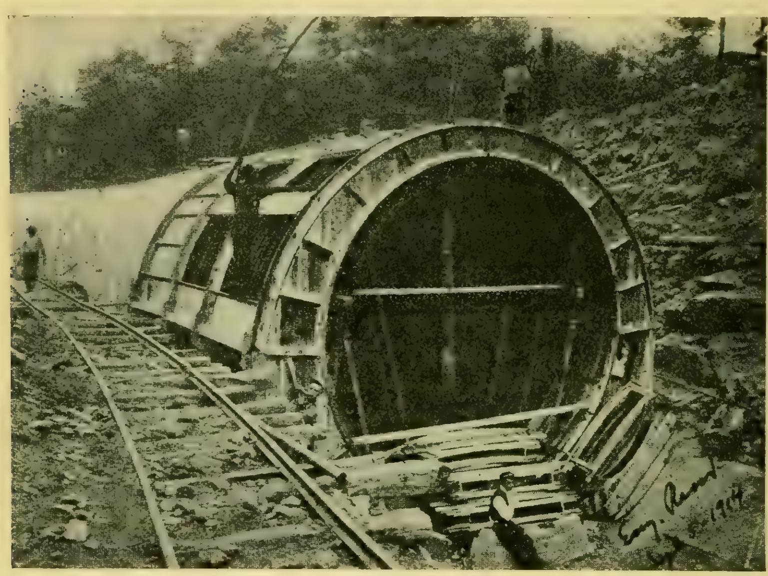


FIG. 69.—Concrete Pipe, Showing Steel Forms for Pouring.

series of experiments, and the values obtained will be found more conservative for larger pipes and higher velocities.

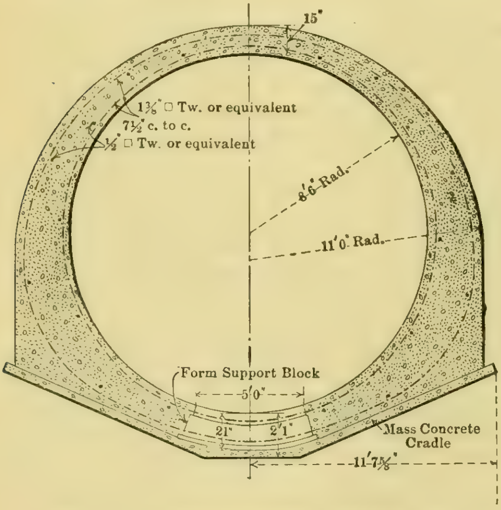


FIG. 70.—Cross-section of Concrete Pipe.

$$h_f = \frac{7.68 \times v^{1.8}}{d^{1.17}},$$

where

h_f = Loss of head in feet per 1000 feet of pipe;

v = Mean velocity of water in pipe, in feet per second;

d = Inside diameter of pipe in inches.

Concrete Pipe. Reinforced concrete pipes (Figs. 69 and 70) for power work are used to a limited extent for low-pressure conduits, but there is every indication

that they may in the future be extensively used in place of open flumes and canals. This will not only tend to increase the total head of the plant, but it will prevent leaves, branches, etc., from falling into the conduit, as they often do when the latter is of the open type.

Concrete pipes are in use for heads up to 150 feet. They are very smooth, being in this respect nearly on a par with woodstave pipe, and thus offer little resistance to the flow of water. They are especially adapted for use where raw material, such as sand, stone or gravel, and cement, is available locally, in which case the pipes are generally manufactured on the job where they are used.

Concrete pipes are sometimes given an oblate cross-section, the flattening being, as a rule, more pronounced on the bottom than on the top. It is claimed that such a form will withstand the water pressure much better than a circular conduit, and for pressure pipes its use may result in a considerable saving in first cost. One of the tubes at the Ontario Power Company's plant at Niagara Falls is of this construction.

2. WATERHAMMER AND SURGE TANKS [1]

Waterhammer. When the gates at the lower end of a penstock are closed and the water column suddenly checked, the pressure immediately rises and may reach very high and destructive values if not provided for or prevented. This rise of pressure is known under the name of "waterhammer."

When the gate begins to close, the pressure rises first at this point, and a pressure wave or vibration begins to travel towards the upper end of the pipe. If the pipe were absolutely rigid, the velocity at which this wave would travel would be about 4650 feet per second, the same as that of sound. On account of the flexibility of the penstock walls, however, the velocity is reduced and may be computed from the following formula:

$$a=\sqrt{\frac{g}{y\left(\frac{1}{k}+\frac{d}{tK}\right)}},$$

where a = velocity of pressure wave or vibration in feet per second;
g = acceleration of gravity = 32.16;
y = specific weight of water = 62.4 pounds per cu. ft.;
k = elasticity of water in compression = 42,000,000 pounds per sq. ft.
d = inside diameter of penstock in inches;
t = thickness of plate in inches;
K = elasticity of penstock material in tension;

[1] See also sections on "Water Conductors" and "Governors."

For steel plate $=4,032,000,000$ lb. per sq. ft. $=$ (28,000,000 lbs. per sq. in.);
For cast iron $=2,160,000,000$ lbs. per sq. ft. $=$ (15,000,000 lbs. per sq. in.)

The value of a varies from 2500 to 4000 feet per second as the size of pipe decreases; and the time required for the pressure wave to reach the top of the penstock and return is evidently equal to

$$T_1=\frac{2L}{a},$$

where T_1 = time required for round trip of pressure wave in seconds;
L = length of penstock in feet.

If the gate is closed instantaneously, or, in a time T, which is equal to or less than $\frac{2L}{a}$, *i.e.*, before the reflected pressure wave has had time to return to the gate and reduce the pressure there, we obtain a maximum excess pressure head which, according to Joukowsky and others, is equal to

$$h_1=\frac{av}{g},$$

while the total pressure will be equal to the above plus that caused by the static head, or

$$H_{\max}=h_0+\frac{av}{g},$$

where $H_{\max}$ = head corresponding to maximum pressure;
v = velocity of water in penstock in feet per second, corresponding to the normal water flow;
h_0 = static head in feet.

It is thus seen that under this condition the pressure rise is independent of the actual length of time of gate closure.

It is impossible for the pressure to rise above this value, $H_{\max}$. The time $\frac{2L}{a}$, therefore, represents the critical time in which the turbine gates may be closed, and it is evident that the time of closure should always be greater than $\frac{2L}{a}$, in which case the waterhammer can never reach a maximum value.

When the time is greater than $\frac{2L}{a}$ the pressure rise is more difficult to determine. Several more or less intricate formulæ have been proposed for its calculation.

One of these is the following, which was derived by Alliévi many years ago, and has been used extensively in the past.

$$h_1 = \frac{Nh_0}{2} + h_0\sqrt{\frac{N^2}{4} + N},$$

where

$$N = \left(\frac{Lv}{gTh_0}\right)^2.$$

The above pressure will also be obtained if the gate is only closed partially, as long as the closing is at such a rate that T is the time which it would require to completely close it.

Alliévi's formula is necessarily subject to certain limitations; for example, for zero duration of closure, it would give an infinite pressure rise, and this cannot be correct because the finite value of maximum waterhammer, as given by the previous formula, has been adequately proved. Those readers who may wish to go into this problem further are referred to a paper entitled " Pressures in Penstocks caused by the gradual closing of Turbine Gates," by N. R. Gibson in the *Proceedings of the American Society of Civil Engineers*, for April, 1919, and especially to the discussions of this paper by eminent hydraulic engineers which appear in succeeding issues of these *Proceedings*.

Surge Tanks. In plants with long pipe lines under medium and high heads, it is often found that not only the pressure rise, but also the pressure drop, will be excessive. In such cases it may be necessary to provide a pressure regulator or surge tank, to equalize the pressure variation. The function of the former is to accomplish this by allowing the water to pass through the regulator as the amount required by the turbine is shut off by the closure of the gates. After the regulator is opened by a rapid closure of the gates, it automatically closes at a rate sufficiently slow to prevent a secondary pressure rise. Different types of such pressure regulators, and their action, are described in the section on " Pressure Regulators or Relief Valves."

Surge tanks, on the other hand, are simply elevated reservoirs connected to the penstocks, close to the turbines. A sudden increase of the penstock pressure will thus cause a rise in the water column in the tank, while a sudden decrease in the pressure will be compensated for by a momentary supply from the tank.

To be most efficient, the surge tank should be located as near the power-house as possible; and, if it operates under atmospheric pressure, its height must evidently be above that of the highwater level in the forebay or storage pond. It is obvious, however, that such an open design would not be feasible for very high-head developments,

and in such cases the surge tank may be of a closed design, the increased air pressure being obtained by the static head. Both open and closed surge tanks may thus be provided, the open type being installed at the upper end of the pipe line, where it passes over the brow of the hill above the power-house, while the closed air chambers[1] would be installed just outside the power-house. For pipe lines several miles in length it is also advisable to provide equalizing reservoirs at intervals along the pipe line, so that changes in the velocity of the water column will be as gradual as possible.

In order to illustrate the action of a surge tank, let us assume a plant supplied by a single conduit of considerable length, having a surge tank located at the end of this conduit on elevated ground above the power-house, as shown in Fig. 12 on page 39. The penstocks leading from the end of the conduit to the wheels are thus relatively short, so that pressure changes in the penstocks due to load changes on the wheels need not be considered.

When the plant is running at constant load, the pressures throughout the system will be stable or quiescent. The elevation of the water in the surge tank will be forebay level, less the drop of the hydraulic gradient at the end of the conduit. The head on the wheels will be the elevation above tailwater of the water in the surge tank, less the penstock losses, proper correction being made, of course, for velocity heads. The instant a load change occurs, however, the pressures in every part of the system from the forebay to tailwater begin to change and, even though no new load change occurs, a considerable period of time must elapse before quiescent conditions are restored. The magnitude and duration of these pressure changes are determined very largely by the design of the surge tank.

The first effect of an instantaneous load increase is the action of the governor opening the wheel gates in proportion to the load change. The wheels demand more water, but the conduit velocity must be increased before the conduit can supply this increased demand. Therefore, the required increment of water is drawn from the surge tank, and the level in the surge tank falls below the gradient, thus creating an accelerating head which increases the conduit velocity until eventually it is sufficient to supply the new demand of the wheels. An instantaneous decrease of load produces the opposite effect; that is, the surge tank receives the water rejected by the wheels, thus building

[1] For the use of air tanks for pipe-line regulating purposes, see Proceedings American Society of Civil Engineers for August, 1917, and the Transactions for December, 1918.

up a retarding head which reduces the conduit velocity until the flow no longer exceeds the requirements of the wheels.

It is apparent that the surge tank performs two important functions, closely related to each other: first, it acts as a receptacle for the rejected flow and as a reservoir to supply the demanded increment; second, it provides the accelerating or decelerating head necessary to correct the flow in the conduit. Obviously, the more effectively the accelerating

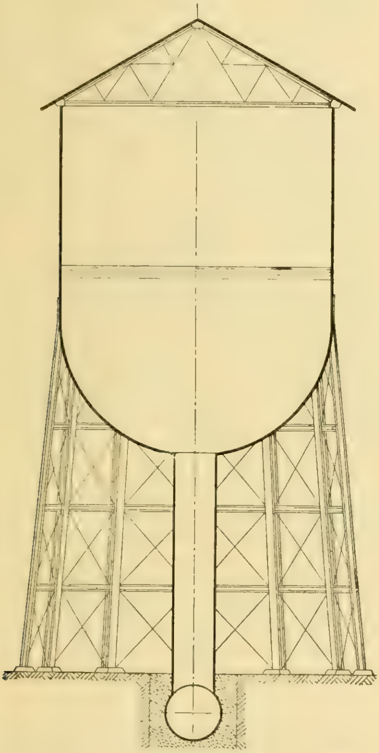


Fig. 71.—Simple Surge Tank.

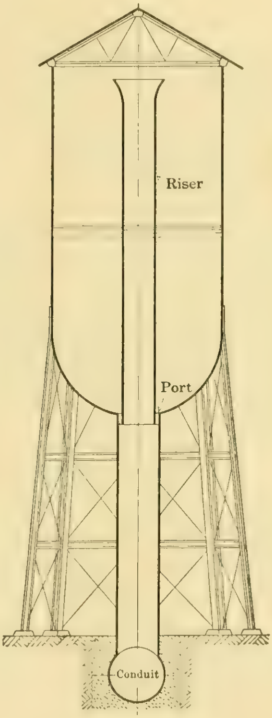


Fig. 72.—Johnson Differential Surge Tank.

or decelerating head is applied, the shorter will be the duration of the surge and the less water will have to be drawn from or received by the tank, resulting in a smaller tank, both in diameter and height.

There are two kinds of surge tanks, the simple and the differential. The former consists simply of an open tank with a pipe connection to the conduit, as shown in Fig. 71, while the differential surge tank (Fig. 72) is in addition provided with a riser of smaller diameter than the connection to the conduit. At the base of the riser there is an

annular port, communicating with the tank. The area of the port is proportioned to suit the conditions under which the tank is to operate, and largely determines the characteristics of the surge. The differential surge tank, which is the invention of Mr. R. D. Johnson, has found a very wide application, because of its many advantages over the simple tank.

When the load is thrown off, with a simple tank, the water level falls gradually. The pressure wave resembles a sine curve, and the accelerating head on the conduit accumulates slowly. The level in the tank falls below the gradient corresponding to the new load before the conduit velocity is accelerated to equal the new demand of the wheels. This starts a surge in the opposite direction and the surges then alternate like a pendulum above and below the new gradient until they are finally damped out by the friction of the conduit. The simple tank is therefore dependent upon conduit friction to make it function properly.

In the case of the differential tank, the water falls first in the riser, establishing in a few seconds a relatively large accelerating head on the conduit. The level in the tank falls slowly, supplying the demanded increment of flow through the ports at the base of the riser. When load is thrown off, the water immediately rises in the riser, establishing a retarding head on the conduit as well as a differential head on the port, which forces the water rejected by the wheels through the port into the tank. The superior merit of the differential tank therefore lies in the capacity to separate its function as an accelerator or retarder of conduit velocity from its function as a storage tank. In the simple tank the corrective action on the conduit velocity accumulates only as fast as the water level changes in the tank, and hence the duration of the surge is much prolonged and the tank has to be made much larger because it must supply or receive water over a longer period.

A discussion of surge tank phenomena is very complicated and beyond the scope of this treatise. Several papers dealing with the subject in great detail have been presented before National Engineering Societies. Among these, the interested reader may consult the following: "The Surge Tank in Water Power Plants," by R. D. Johnson in *Transactions American Society Mechanical Engineers*, 1908; "The Differential Surge Tank," by R. D. Johnson in *Transactions American Society Civil Engineers*, Vol. LXXVIII (1915); "Surge Tanks," by B. F. Jakobsen, in *Proceedings American Society Civil Engineers* for April, 1922.

3. GATES AND VALVES[1]

Requirements. For the control of water flow in hydro-electric developments, gates and valves are generally used. They may be either of the sluice gate, gate valve, or cylindrical type; and the selection of the type, as well as the number required, is governed by the nature of the development. For example, in low-head plants, only one set

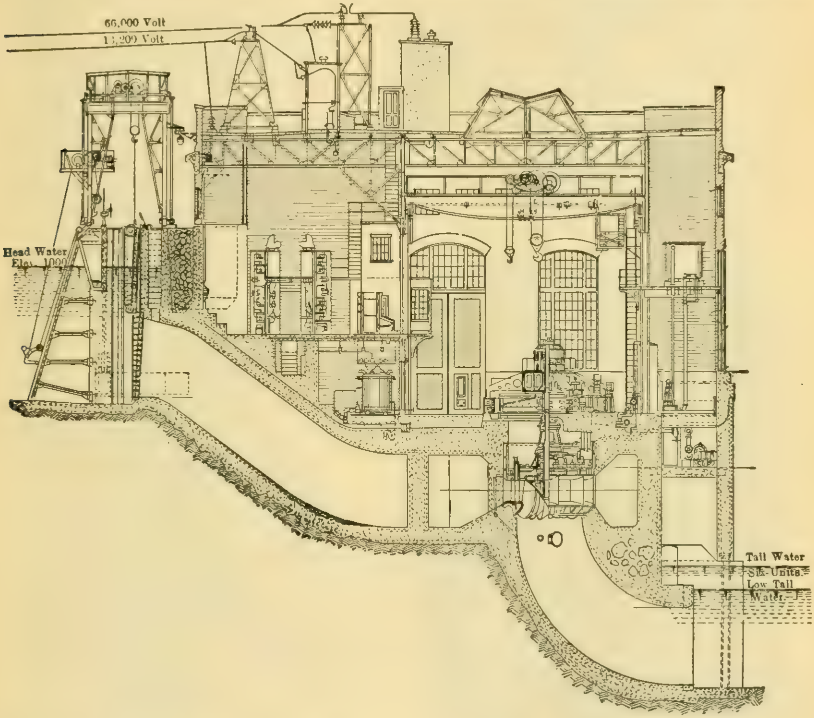


Fig. 73.—Sectional Elevation of Power House, Turners Falls Power and Electric Company, Showing Headgate Arrangement.

of sluice gates are, as a rule, needed, these being installed in front of the turbine intakes, either in a gatehouse, as in Fig. 93, or outside the power-house building at the dam structure, as in Fig. 73.

For high-head developments, however, two and sometimes three sets of controlling devices are required, depending on the pipe-line arrangement. This duplication is necessary in order that the water may be properly shut off in case of an emergency, such as would arise if one of the valves should become damaged or stick. In such plants,

[1] See also section on "Flashboards."

sluice gates are installed as headgates at the forebay or reservoir intake, while gate or cylindrical valves are provided in the pipe line at a point close to the wheel casing.

The gates should be of sufficient size to pass the required maximum flow of water, and also of sufficient strength to withstand the shocks and excessive pressures resulting from a quick closing in case of emer-

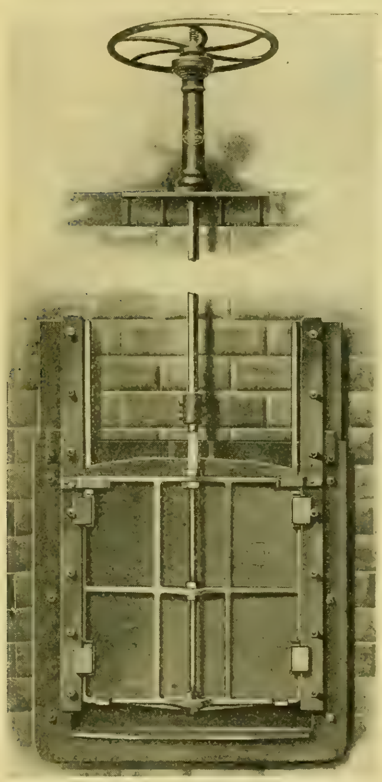


Fig. 74.—Rising Stem Sluice Gate with Floor Stand. (Ludlow Valve Mfg. Co.)

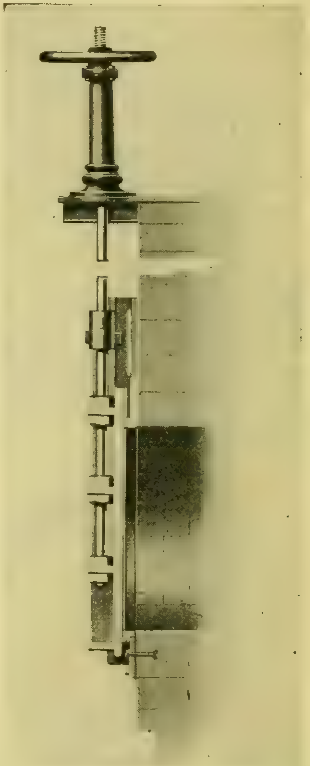


Fig. 75.—Rising Stem Sluice Gate. Side View of Gate Shown in Fig. 74.

gency. This is a point which must be considered in determining the minimum time in which the gates may be closed. As mentioned under the chapter on "Waterhammer and Surge Tanks," the longer time allowed for closing the gates the less will be the pressure caused by waterhammer.

Sluice Gates. These may be either of structural steel or cast iron, the former generally being used for large intake openings. With low-head developments, these openings are now generally divided into a

number of vertical sections in order to insure a more even distribution of the water to the speed ring of the turbine; this, of course, also very considerably reduces the size of the gates, one set being provided for each section. Sometimes the sections are also divided horizontally, as shown in Fig. 11, in order to still further reduce the size of the gates. At the junction of the upper and lower sections there is a reinforced

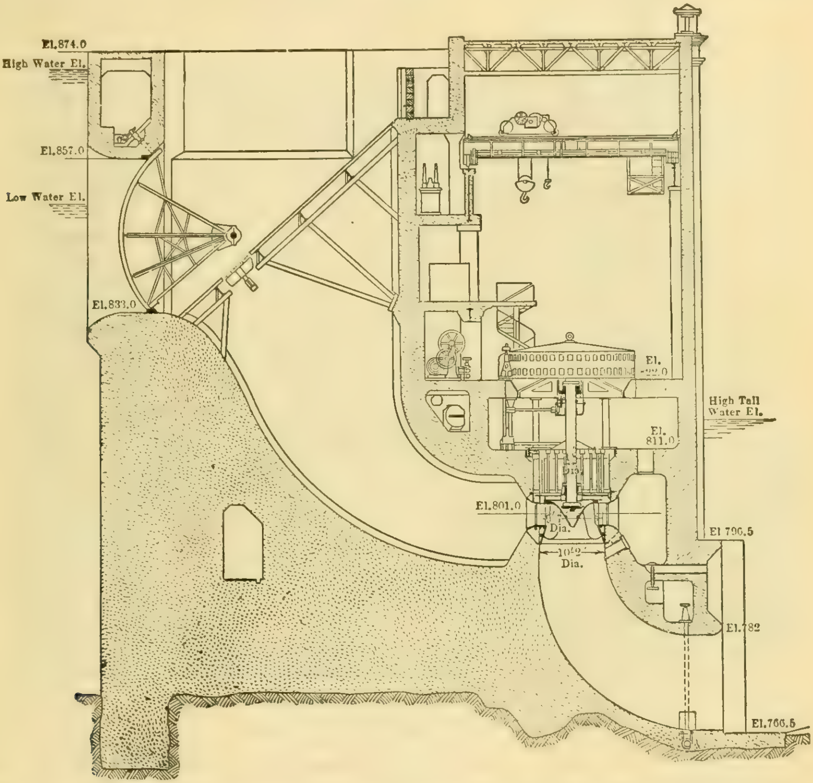


FIG. 76.—Sectional Elevation of Power House of the Hydro-Electric Company of West Virginia, Showing Application of Tainter Gate.

concrete beam which serves as a support and as a seal. The two-gate sections are provided with separate guide slots so that they may be manipulated independently. This type of gate is generally lifted by means of chains.

The gates shown in Fig. 73 are the Broome type and are constructed of heavy steel plates run on a continuous chain of rollers between the tracks on the gates and guides. A gantry crane, electrically driven and running on the head wall, operates the gates. This crane also carries a mechanical rack-raking device.

Gates which are raised or lowered by means of stems may be either of the rising or non-rising stem type, the former being preferable at intakes where there is no danger of the operating stands being submerged, and where the rising stem may serve as an indicator of the gate position (see Figs. 74 and 75). For gates which are installed in diversion dams for sluicing off excess flood water in forebay ponds or reservoirs, the non-rising type is preferable, as it may be submerged without being damaged by floating ice.

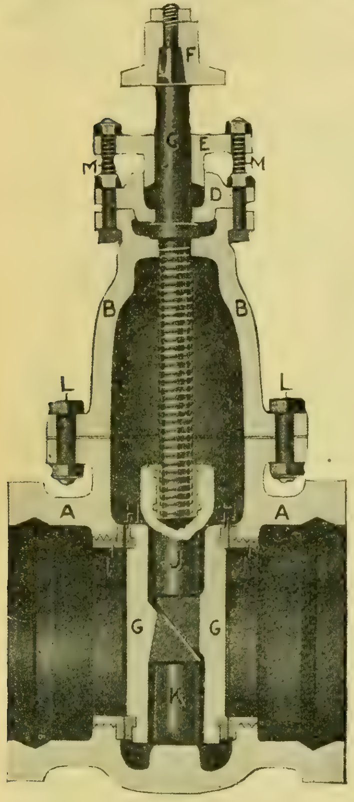


FIG. 77.—Ludlow Bronze Mounted Double Gate Valve with Bolted Stuffing Box.

A—Case. B—Cover of Bonnet. C—Stem or Spindle. D—Packing Plate or Stuffing Box. E—Stuffing Box Gland or Follower. F—Stem Nut. GG—Gates. H—Gate Rings. I—Case Rings. J—Top Wedge. K—Bottom Wedge. L—Throat Flange Bolts. M—Stuffing Box or Follower Bolts.

Tainter Gates. This type of gate is occasionally used for controlling the water passages to the wheel chambers in low-head developments, the methods of application being shown in Fig. 76. It is, however, more used in connection with diversion dams.

Gate Valves. There are numerous different designs of gate valves, the details of one of the most improved designs being illustrated in Fig. 77. It is intended for high pressures and consists of the stem, a double disc and two bevel-faced wedges, the wedges being entirely independent of the discs and working between them.

By the action of the stem, which works through a nut in the upper wedge, the discs descend parallel with their seats until the lower wedge strikes the stop in the bottom of the case. The discs and upper wedge, however, continue their downward movement until the face or bevel of the upper wedge comes in contact with the face or bevel of the lower wedge. The discs then being down opposite the valve opening, the face of the upper wedge moves across the face of the lower wedge, bringing pressure to bear on the backs of both discs, from central bearings, thus forcing them apart and squarely against their seats.

In opening the valve, the first turn of the stem releases the upper wedge from contact with the lower wedge, thereby instantly releasing both discs from their seats before they commence to rise.

All gate valves and sluice gates should be fully bronze-mounted to prevent corrosion. That is, the disc and seat rings, as well as the threaded portion of the stem, the operating nut and the wedging appliances, should be made of bronze.

Where the water pressure is very great, by-pass valves may be pro-

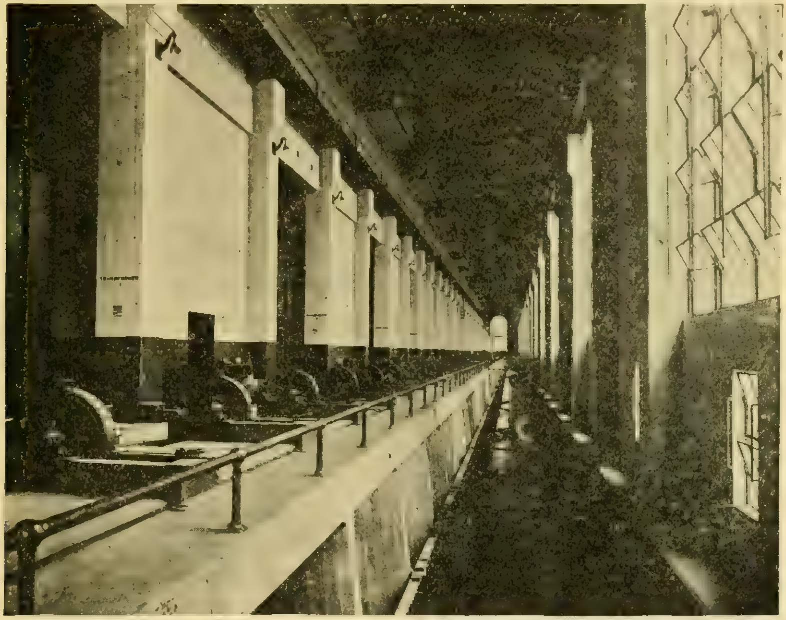


FIG. 78.—Gatehouse, Showing Gate-lowering Mechanism. Mississippi River Power Company.

vided for equalizing the pressure on both sides of the valve before it is opened.

Operation and Control. Sluice gates and gate valves may be operated either by hand, water or electrically, the two latter methods being used extensively, resulting in a saving of labor. This is evident by considering that some large valves would require a long time to close by hand. When sluice gates are installed in gatehouses a traveling crane is often provided for lifting them. Their closing is then done through their own weight, and brakes are installed for regulating the same (Fig. 78). Whatever method of operation is chosen, it should be simple and positive in its action.

There are numerous hand-operated lifting devices, such as rack-and-pinion with an operating lever, windlass, floorstands with threaded gate stems and operating wheels, etc. Gear trains should always be provided where there is considerable pressure on the gate; otherwise, it may be impossible for the operator to start the gates especially when they have been closed for some time. Arrangements are generally made, however, for shifting the hand-wheel directly to the stem after the gate has been opened slightly, in order that the opening may be accomplished more rapidly. Rollers and ball bearings are also sometimes provided, either with the discs or the lifting devices, so as to reduce the friction.

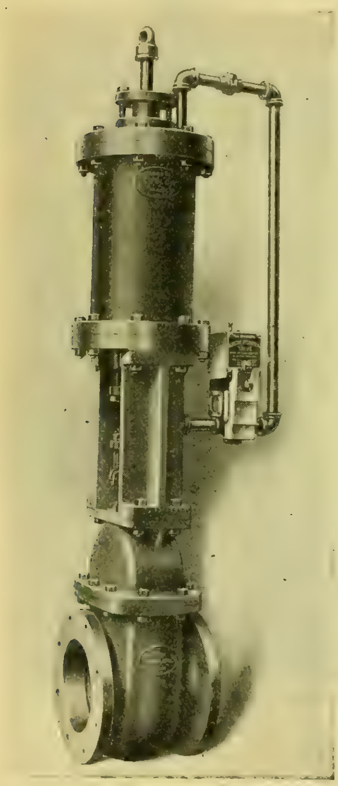


Fig. 79. — Ludlow Hydraulic Operated Cylinder Valve with Electric Control.

Gate valves may also be operated by hydraulic cylinders. The regulating valve consists of a flat valve which is operated by a piston, this in turn being moved by releasing the pressure on either side by means of small poppet valves which may be operated by hand or electrically from any convenient point. A valve of the latter type is shown in Fig. 79.

Cylinder valves are, as a rule, more economical for smaller sizes, while for larger sizes the electric-motor-operated valve (Fig. 80) is to be recommended. Such valves are very reliable and can be closed in a comparatively short time. Besides this, remote control from the main control board in the power-house can readily be provided.

The service of valve motors is exceedingly intermittent and may vary from comparatively short intervals, such as once every hour, to weeks or even months. When the apparatus at the end of long periods of idleness, is called upon to operate, it must perform its function without fail, and must, therefore be designed accordingly, totally inclosed motors of a moisture-proof design being preferable. Metalline bearings are generally used, as the motors may be mounted in any position from vertical to horizontal. Because of the intermittent nature of the service,

efficiency or power factor need not be considered, the main consideration being reliable operation.

The proper size of a motor for driving a valve will vary with the duty and conditions under which the valve operates. A small valve may only require a 1-horsepower motor, while very large valves require up to 25-horsepower motors. The size of the valve, however, is not the only factor determining the required motor capacity, which also depends to a very large extent on the pressure on the valve and the time of opening.

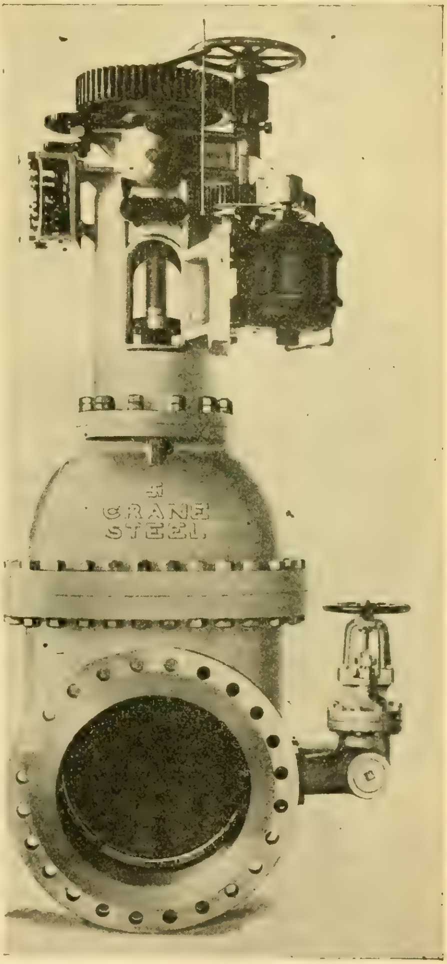


Fig. 80.—Heavy Pressure Motor-operated Gate Valve, Showing Motor Equipment and Limit Switch.

The torque requirement varies greatly during the operating cycle. It is maximum shortly after the time of unseating the valve; that is, after the wedges have been released and the actual motion begins. It then drops somewhat until the valve has opened about one-fourth, after which it take comparatively little power to complete the opening, as the pressure on the valve is then comparatively small. When the valve is being closed, friction alone has to be overcome in starting and there is no pressure on the valve until it has begun to close. The torque is therefore not very high until the valve is about three-fourths closed, after which the pressure causes the torque to increase rapidly. At the end of the closing cycle the torque does not, however, reach the value it did during the period of starting.

Valve motors are, therefore, generally rated for maximum starting torque and either direct or alternating current motors may be used.

The former are mostly compound wound with a sufficient shunt field to limit the speed at light load. With the latter the squirrel-cage induction motor seems to be most widely used for small and medium-size valves, principally on account of its simplicity. It should be designed with a high-resistance rotor to increase the starting torque, and it is generally found necessary to select a motor somewhat larger

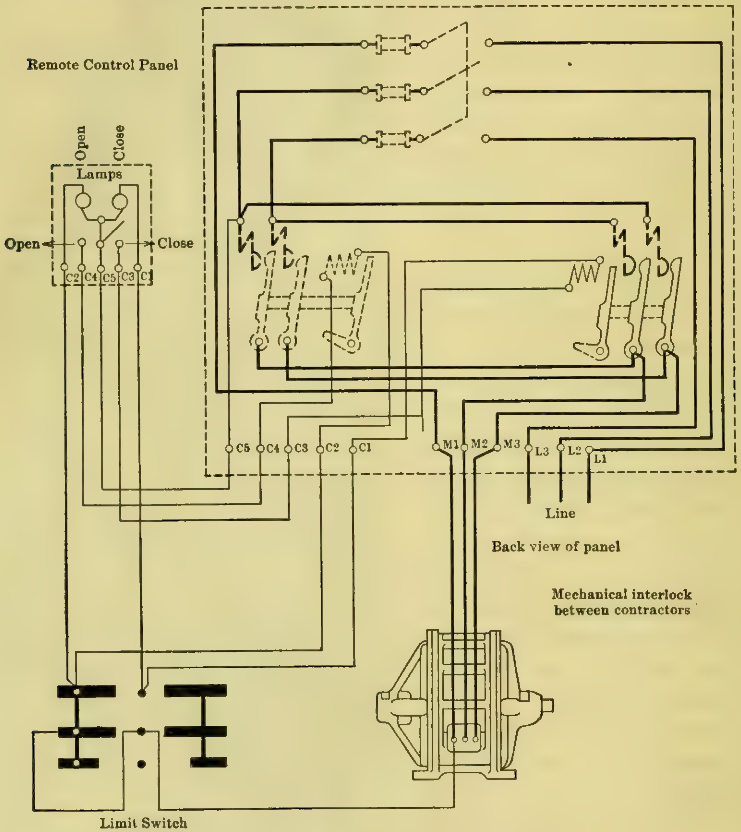


FIG. 81.—A.C. One-station Remote Control Equipment.

than would be necessary with a compound-wound direct-current motor to perform the same duty.

With certain valves it becomes necessary to overcome the sticking due to wedging action when opening, and the drive is therefore provided with a "lost motion" so as to give a hammer-blow. For alternating current motors, this is furthermore of value in that it permits the motor to speed up somewhat and gain in torque before the load comes on, the maximum torque, as a rule, occurring slightly above zero speed.

Valve motors are generally thrown directly on the line, and the control is accomplished by means of contactors for remote control and large equipments. For hand control of smaller equipments, ordinary knife switches are sufficient. Fuses give better protection than automatic circuit breakers, in that they will protect against a stalled motor but will not blow during start or running.

Limit switches, which will open the circuit when the gate has reached its limit of travel, should always be provided. Such switches

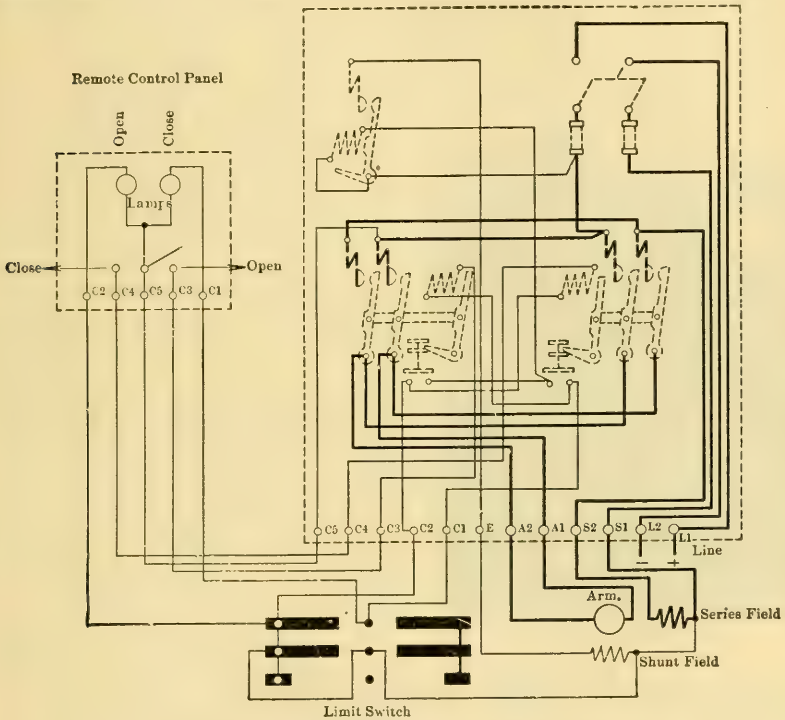


FIG. 82.—D.C. One-station Remote Control Equipment.

are geared to the valve stem and arranged to open the contactors at a predetermined point of travel of the gate in either direction. Provision is also made for indicating the open or closed valve positions on the control board by means of two lamps. When only one lamp burns it indicates open or closed valve position, as the case may be, while both lamps burn in any mid position.

In some cases it is found desirable to cause the motor to slow down and seat the valve under reduced torque and speed, in order to have more or less constant conditions at the time of closing. To accomplish

this, suitable resistors are connected by contactors to form a series and multiple circuit with the direct current motor armature. This operation is performed at any desired part of the travel, by means of the limit switch. The multiple resistor acts as a dynamic brake and immediately brings the motor speed down to the desired value, and the valve is seated under direct motor torque. When the valve seats, the current increases through the motor, and a thermal overload relay trips the motor circuit breaker after a short time. The operation thus eliminates the inertia forces of the rotating parts, by reducing the speed, and avoids the possibility of strain to the mechanism by seating the valve when these parts are running at high speed.

Somewhat similar results may be obtained in the case of alternating-current motors, by the insertion of resistors in the motor lines. This resistance is controlled by contactors and limit switches, as described above.

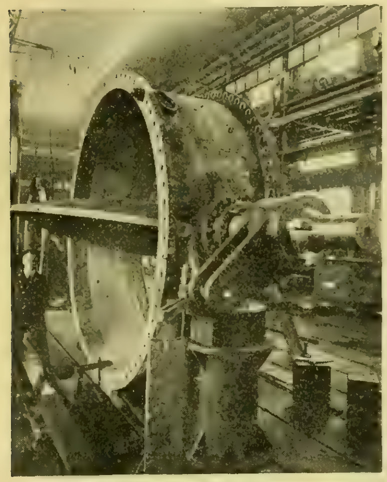


Fig. 83.—Pivot Valve.

Connection diagrams for D.C. and A.C. remote-control equipments are shown in Figs. 81 and 82. These are for single-station control; for multiple-station control push buttons are substituted for the single-pole double-throw pilot switch.

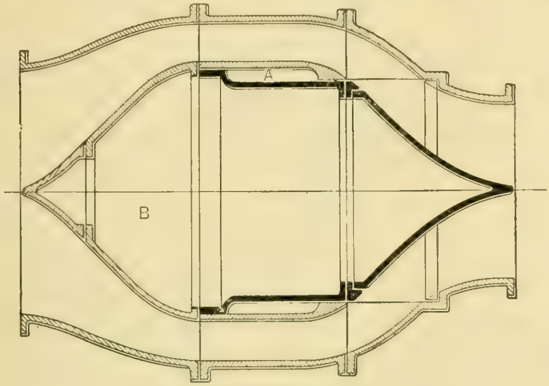
Pivot Valve. A type of valve which has been used in a number of large plants, for the purpose of shutting off the turbine from the penstock, is the pivot or "butterfly" type of valve, illustrated in Fig. 83 This type of valve is simple in construction and takes up very little space. It may be either hand or electrically controlled, or a hydraulic-operating cylinder may be used.

The Johnson Hydraulic Valve. The Johnson Valve, first introduced for commercial use, in water-power plants in 1910, applies the needle valve principle to the problem of controlling the flow of water in pipe lines and conduits. Its use has grown steadily and is now generally adopted in practically all the large and important installations.

It consists, in general, of a circular body surrounding an internal cylinder, closed at one end and connected to the body by radial ribs, in which a pointed plunger or needle operates, making contact with a seat in the neck of the body to close the valve (Fig. 84). The pressure

used to move the plunger is the pipe-line pressure in the body of the valve itself. The flow of the water through the valve is smooth and free from disturbances. It is perfectly tight, and the loss of head is practically negligible. No by-pass is required for its operation.

Referring to Fig. 84, it is seen that these valves have a differential plunger which, in combination with the internal cylinder, forms two



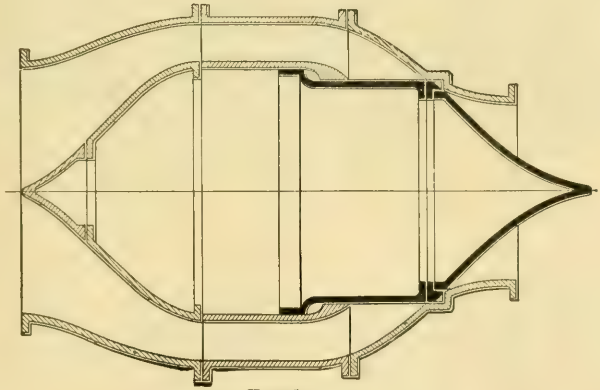


Fig. 84.—Type A, Johnson Hydraulic Valve.

operating chambers, *A* and *B*. The plunger is closed by admitting pressure from the waterway to *B* and exhausting *A* to the atmosphere. It is opened by reversing the operation.

There are several types of control used with these valves. One is designed primarily for hand operation and involves a reciprocal action between the control mechanism and the valve plunger, as a result of which the plunger follows the control valve at the same rate and auto-

matically corrects any tendency to overtravel. No load is imparted to the control mechanism.

With another type of control the rate of opening and closing the valve and the opening and closing characteristics are automatic and in no way dependent upon the skill or experience of the operator. It is hydraulically operated and may be connected to any number of control stations. This control has many interesting automatic characteristics. It thus cracks the valve open to prime the wheel casing, dispensing with the by-pass; and when pressure is established in the wheel casing, the valve resumes and completes the opening stroke. The rate of opening is adjustable. It also damps the end of the closing stroke to prevent waterhammer.

If it is necessary to close the valve, with the wheel gates open, or if the wheel casing bursts, serious waterhammer will result, unless the closing characteristics of the valve are adjusted to the velocity of flow in the penstock and the length of the penstock. If the valve is thus closing with the wheel gates wide open, it will close a considerable portion of the stroke before the velocity in the penstock is reduced at all. At first the only effect is to speed up the flow through the valve opening, and it is immaterial how fast the valve closes up to the point where it begins to reduce the flow in the penstock. As soon as the velocity through the valve approaches its maximum value, the control should automatically slow down the closing stroke. The rate of closing, both before and after damping, are independently adjustable.

In case of a serious break in the wheel casing or the water passage beyond the valve, resulting in a drop of pressure therein to a point much below normal, the valve will close automatically and the closing characteristics will be exactly the same as if it had been controlled as explained above.

Figure 85 shows the Johnson 14-foot valve, as installed in connection with the 55,000 horse-power turbines in the Queenston plant at Niagara Falls, Ontario.

Air Valves. In addition to sluice gates and gate valves previously described, air valves are often required in connection with the pipe lines of hydro-electric developments. These may be of two kinds: the automatic lever and float valve, and the automatic poppet valve.

The former is for use on pipe lines which follow the contour of hilly country, where air may accumulate at high summits and obstruct the flow of water. The valve is connected to the outside of the pipe at its highest point or points; and when air takes the place of water about the float in the valve chamber, the float, which is attached to a lever, drops,

thus opening a small valve, allowing the air to escape. As the water returns, it lifts the float, thereby closing the valve.

The poppet valve, on the other hand, is intended for use on pipe lines, to permit air to enter when water is being drawn off, and thus

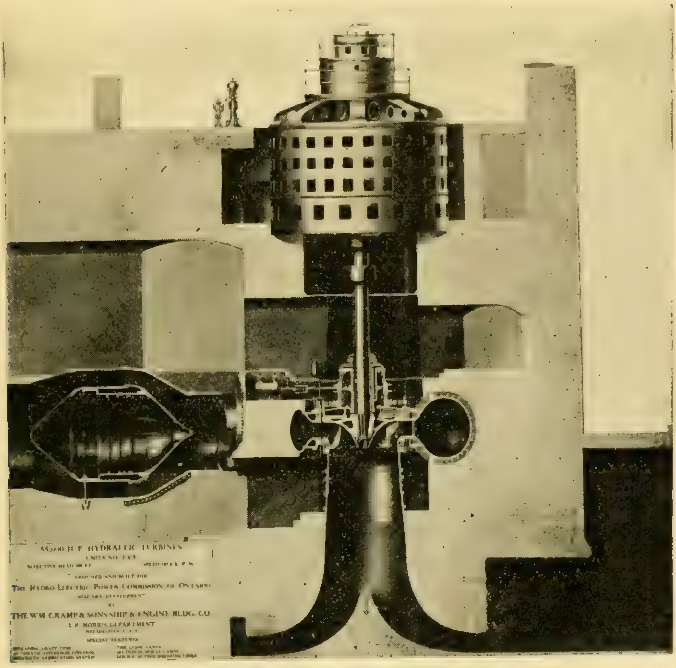


FIG. 85.—Johnson Fourteen Feet Valve as Installed in Connection with the 55,000 Horsepower Turbines in the Queenston Plant, Niagara Falls, Ontario. Operating Head, 305 Feet.

eliminate any danger of collapse from vacuum forming in the pipe lines as, for example, when the head gates are closed. Similarly, they may be provided to allow air to escape when the pipes are being filled. The valve remains open until the water reaches and lifts the copper float and closes the same, after which it remains closed while the pressure is on.

CHAPTER V

STORAGE RESERVOIRS [1]

MANY watersheds have some natural storage features tending to equalize the stream-flow as compared with the rainfall, while with others surplus water in times of high flow can be held back for use in times of low flow only by the construction of artificial reservoirs.

Storage and Pondage. The impounding and accumulation of surplus water, which may be utilized when needed, is termed either "storage" or "pondage." The former generally refers to reservoirs located on a watershed at some distance from the power-house, and where large quantities of water may be impounded for use during the dry season. "Pondage," on the other hand, refers to the storage for taking care of the daily fluctuation in the load curve; if there were no pondage, canals, flumes and pipe lines would have to carry the peak flow of water instead of the average. It is often the case that the average demand for power during twelve or fourteen hours of the day is twice as great as the demand for the remaining ten or twelve hours. The small volume of power required during a portion of the day permits an accumulation of water at the power dam itself, which can be used as a reserve force to meet the higher demand during the other portions of the day. Thus, a stream that during the twenty-four hours might develop a continuous horse-power would, if relieved of half of the demand for half of the day, be able, with small pondage, to supply considerably more than the average during the remaining portion of the day.

The importance of pondage should, however, not be exaggerated, as it can only be utilized at the expense of operating head; to counteract this effect, it is possible to provide temporary flashboards by which the normal level may be raised several feet.

The storage is, however, of the greatest importance, as it will usually greatly increase the earning capacity of any development.

Limitations to Storage. There is, however, a limit to storage, and in no case can sufficient impounding be maintained to give to any stream

[1] See also section on "Water Storage."

the power representing anything like its maximum flow. The excess run-off from any watershed varies greatly from year to year, and it is generally considered to be the best practice to base the reservoir capacity on the run-off for the minimum year; the practice of impounding the water in years of heavy run-off and holding it over in storage to dry seasons is generally considered uneconomical, on account of the loss due to evaporation, and for other reasons. In general, there are two factors determining the practicable amount of storage. The first consideration is usually the topography of the locality. In some localities a sufficiently high dam may be built at a very reasonable cost, and it may provide storage for an immense volume of water and thus greatly enhance the minimum power of the stream. In other cases, the conditions may be entirely the reverse. A further practical consideration is the value of the land. Even with favorable topographic conditions, the cost of acquiring lands to be flooded may be so great as to make any great amount of storage impracticable.

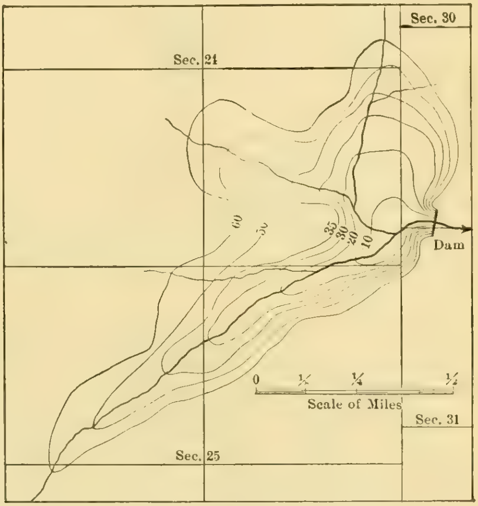


FIG. 86.—Contour Map of Reservoir Site.

Location of Reservoir. The relative location of the proposed reservoir site in the drainage area must, of course, also be considered, and likewise its location with respect to the point of distribution, so that proper outlets and conduits can be provided at a reasonable cost.

Before accurate surveys are justified, it may become desirable to determine approximately the quantity of water that a proposed reservoir may hold. This is usually done by means of contour maps, the topography being taken by means of transits and stadia, and the contours plotted as in Fig. 86. The area is found by planimeters, and the volume by multiplying the vertical distance between the contour levels by the mean area of the sections. A certain dead space must be allowed at the bottom of the reservoir, as it is not advisable to draw off the water from the bottom level on account of the silt and mud which accumu-

late there. The following table gives the capacity of the reservoir site outlined in the above figure:

TABLE XXXV

RESERVOIR CAPACITY

Height of Water above Bottom in Feet.	Area in Acres.	Capacity of Section in Acre-feet.	Total Capacity in Acre-feet.
10	10	0	0
20	36	230	230
30	74	550	780
35	110	460	1240
50	188	2235	3475
60	274	2310	5785

The unit measure of stored water is generally the "acre-foot," representing 43,560 cubic feet, and the curves in Figs. 87 and 88, show the kilowatt-hours for different acre-feet storage on various heads, and vice versa, the over-all hydro-electric efficiency being assumed to be 65 per cent.

It has also been proposed to adopt the "square-mile foot" as a unit for expressing large quantities of stored water. This is equivalent to 27,878,400 cubic feet or, 640 acre-feet.

The building of storage reservoirs involves many engineering problems, the most important being the dam construction, which was treated in Chapter III. Spillways must be provided for discharging excess flood waters; and, with earthen dams or masonry dams of considerable height, outlets, in the form of tunnels or otherwise, are generally provided some distance from the dam, to prevent any possibility of damage to the same. Provision must also be made for outlets at the bottom of the reservoir, so that excess accumulation of silt and mud may be sluiced away.

Outlets. Under low heads, the requirements of reservoir outlets are satisfactorily met by the various forms of slide gates, but high heads present greater difficulties, due to the enormous amounts of power involved in the discharge. The close regulation of the discharge also adds difficulty to the problem. It requires that the movable port of the valve be constantly in contact with the highest velocity of the water, since it is at this point that regulation must be effected. Silt also contributes its share of the difficulty, for not only does it erode the metal surfaces by sand-blast action, but in many cases it

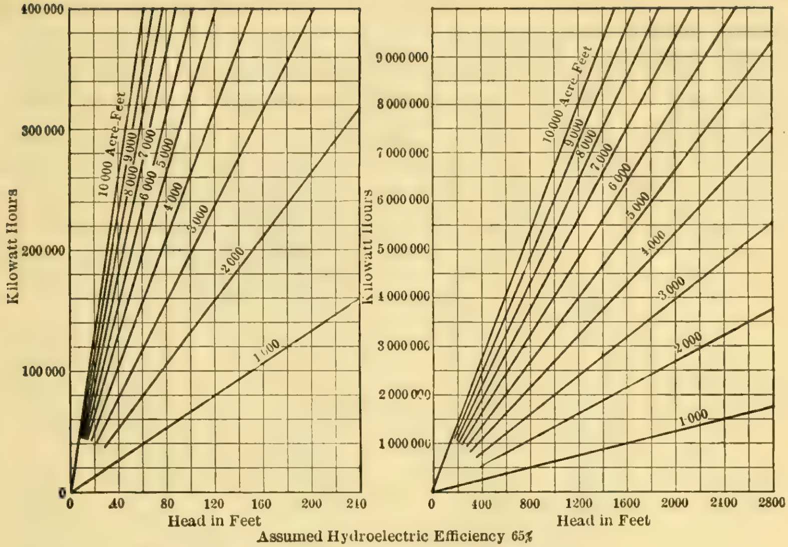


Fig. 87.—Curves Showing Kilowatt Hours for Different Acre-feet Storage on Various Heads.

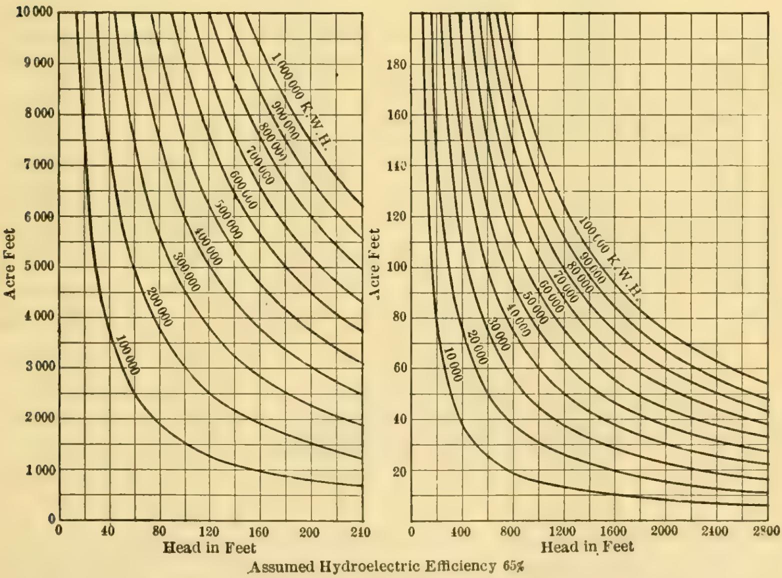


Fig. 88.—Curves Showing Acre-feet Storage Required for Different Kilowatt Hours on Various Heads.

deposits a scale which fills up the close clearance spaces and causes sticking of the valve.

It is difficult to generalize as to the type of gate to use; but it is safe to say that only comparatively small slide gates will operate

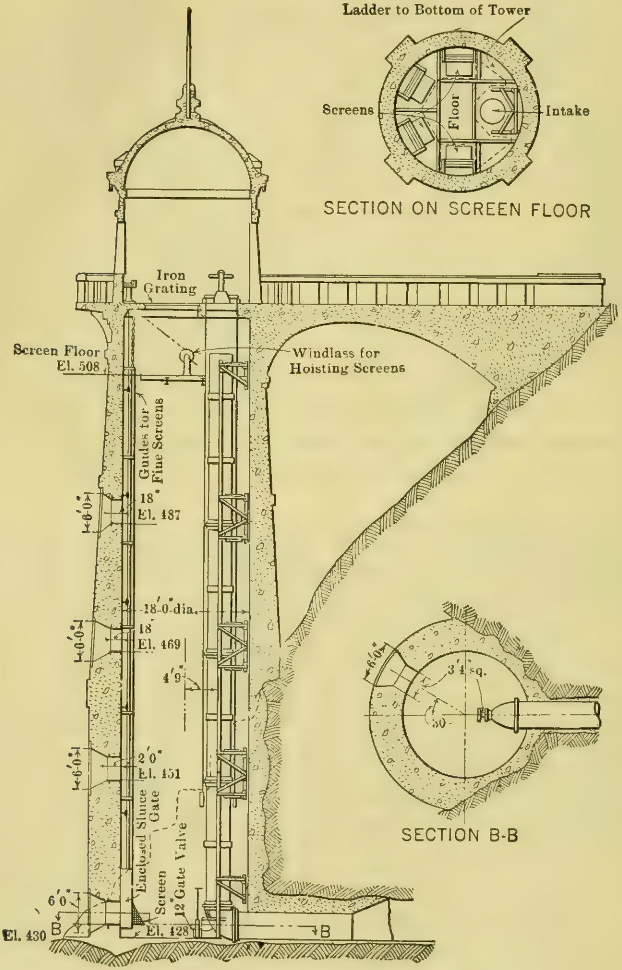


Fig. 89.—Concrete Outlet Tower.

satisfactorily under heads in excess of 50 feet. It is possible, however, to provide outlet opening at different elevations, where the depth of water is considerable. The upper openings should then be used when the water level is highest, and the others in order as the water is drawn out and the level lowered. In this manner the pressure and erosive

effect is reduced, while, on the other hand, there is less danger of a shut-down in case there were only one gate opening at the bottom, which would be liable to be clogged up by silt and mud.

Such intakes are sometimes built in the form of towers, a typical design being shown in Fig. 89. There are four square intake openings placed from 18 to 21 feet apart vertically, and at angles of 60° to each other in the plan. The openings are provided with screens and sliding steel gates which are controlled from the operating floor. There is also a secondary intake placed entirely inside the tower, consisting of a standpipe 42 inches in diameter, built up in four separate sections. Each section has a conical seat at the upper and lower ends, and is seated on the one next below, the bottom section seating on a heavy cast-iron elbow which connects with the intake pipe. The water entering the intake openings in the tower wall must, therefore, pass through the top of the vertical standpipe, and in this manner any silt or mud is prevented from being carried along. As the water level goes down, sections of the standpipe are removed. This is readily accomplished by means of a lifting gear, the pipe sections being closely guided.

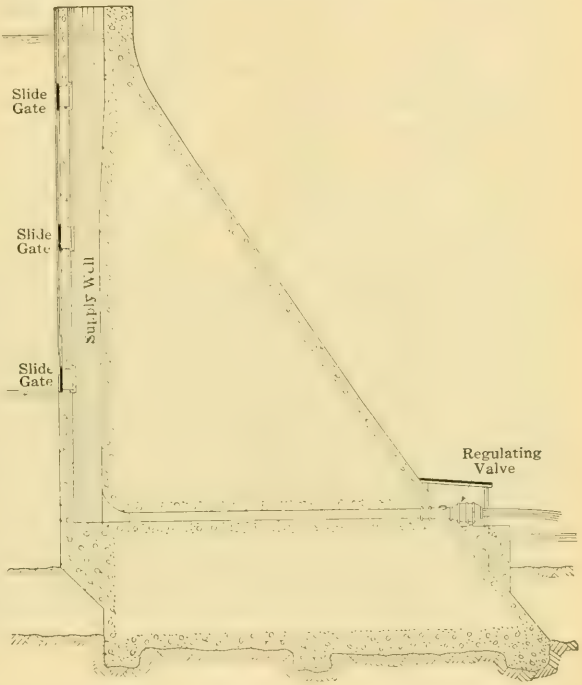


Fig. 90.—Typical Arrangement of Johnson Regulating Needle Valve to Storage Reservoir Outlet.

It is now generally conceded that the needle valve, as described under "Gates and Valves," is admirably adapted for outlets of large reservoirs, as it will discharge the water in a smooth jet at all openings. and unless the discharge is free from disturbance, vibration will certainly result. It is claimed that the best location of this type of valve

is at the downstream face of the dam, the water being supplied to the valve by a conduit through the dam. The valve in this position has a greater capacity than if installed on the upstream side where it would cause a greater contraction of the water in the conduit. This contraction may also cause such a violent disturbance as to tear the metal lining from the conduit. A valve located at the downstream end of the conduit is, of course, also readily accessible, which is of the greatest importance in connection with regulating valves.

Figure 90 shows a typical arrangement of a storage reservoir outlet with a needle regulating valve located at the discharge end of the conduit, the discharge in this case being directly into the air to the river. A supply well is provided in the dam structure, to which water is admitted through slide gates. These are located at several different elevations, in order that they may be successively operated under low pressure as the water level in the reservoir is drawn down.

Seepage and Evaporation. Consideration must also be given to seepage, and extreme care should always be taken to insure imperviousness of the reservoir bottom. It may thus be necessary to strip the top soil until impervious strata are reached, while fissures may have to be closed.

Evaporation must necessarily be taken into account when determining the reservoir capacity. This loss can, however, not be regulated, although a deeper and narrower reservoir will have less evaporation loss than a wider and shallower one.

CHAPTER VI

POWER-HOUSE DESIGN

1. BUILDING

General Design. The design of power-houses differs greatly, depending on the conditions which are to be met. It is affected, to a very great extent, by natural conditions, such as the location with respect to the stream, the condition of the soil, etc. Low and high-

FIG. 91.—Power House, Mississippi River Power Company, Keokuk, Iowa.

head developments require different types of turbines, and these may furthermore be of a horizontal or vertical construction, necessitating entirely different layouts. The number and capacity of the generating units is obviously a determining factor; and the location of the development is generally such that a high-tension transmission is necessary, and provision must therefore be made for housing the transforming and high-tension switching apparatus. In many instances, however, these are installed outdoors, resulting in a considerable saving in the cost of installation, especially with very high voltages.

In designing the building, the arrangement of the apparatus should naturally be given first consideration, but this does not mean that the architectural features should be neglected. It is not necessary

that the building should be too ornamental. Simplicity in design and harmony with the surroundings are very desirable, in order that the structure may attract the attention of visitors, without marring the scenic effect. Figures 91 and 92 are good examples of pleasing architecture.

A hydro-electric power-house building is generally divided into two longitudinal bays, a front or main bay, containing the turbines and generators, and a rear bay containing the transformers, switching apparatus, etc. (see Fig. 93). The two bays are separated either by a wall or by a row of supporting columns, and the rear bay is divided into two or more floors, and these in turn into various rooms or compartments.

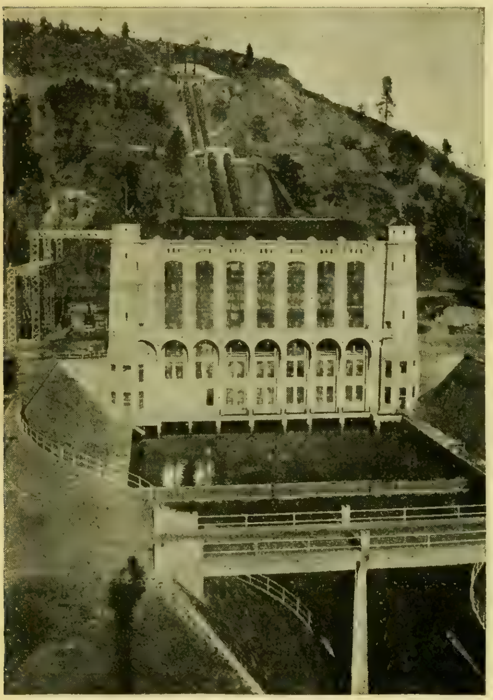


Fig. 92.—Pitt River Power Development No. 1 of the Pacific Gas & Electric Co., California.

Substructure. In modern low-head developments, where vertical turbines are used, the substructure not only serves as foundation for the superstructure of the building, but is really the hydraulic structure, in that the intakes, turbine casings and draft tubes are molded directly in the concrete. In such plants, one or more basements or tunnels are necessary for providing access to the turbines, and for housing the various oil-pressure pumps for the governors and bearings.

Where the floors must carry heavy loads, or when they are to support the generator frames, bearings, etc., they must be heavily reinforced with I-beams and supported by concrete piers.

With horizontal turbines, no basement is needed, although tunnels are usually installed below the main floor, for cables, oil and water piping, etc. Ventilating ducts for carrying fresh air from the outside to the different generators are also essential, especially in low-head

plants with slow-speed units. This subject is treated more fully under "Ventilation."

Foundation. The most important part of the building is the foundation, and careful soundings must be made to ascertain the char-

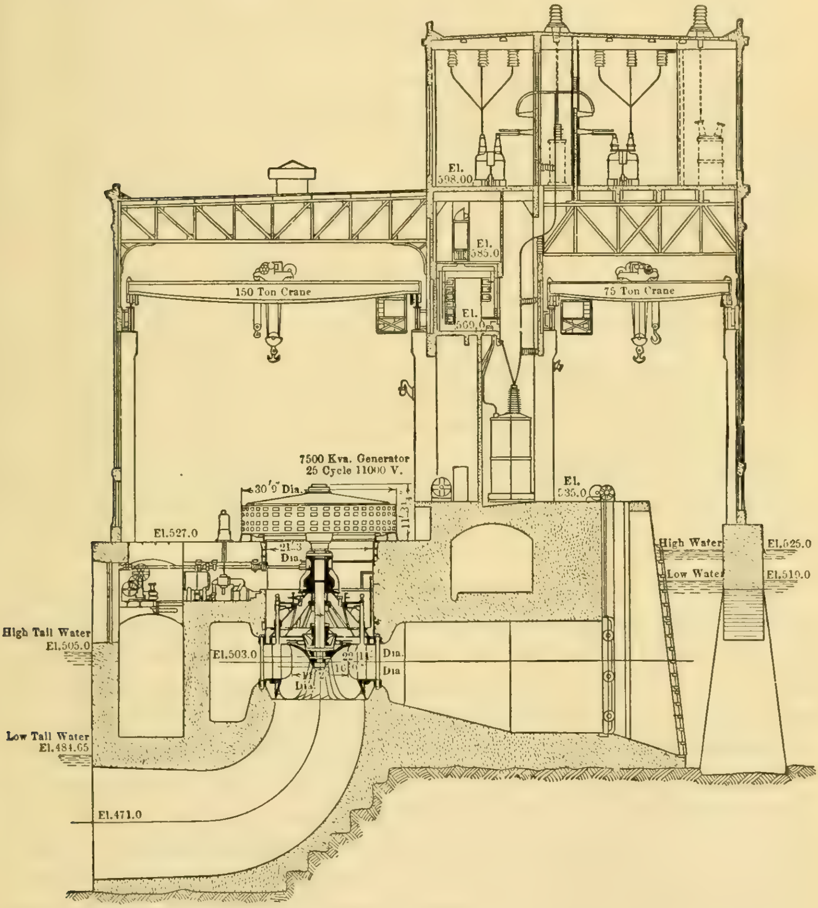


FIG. 93.—Sectional Elevation of Power House, Mississippi River Power Company, Keokuk, Iowa.

acter of the underlying strata. If bedrock is found within moderate depth, the foundation should be carried down to the same. For all soils there is a certain safe bearing load, and if this is exceeded the structure supported thereby is apt to settle. The safe loads usually allowed in this country are given in the following Table XXXVI:

TABLE XXXVI

SAFE BEARING POWER OF SOILS [1]

	Bearing Power in Tons per Square Foot.	
	Minimum.	Maximum.
Rock, hardest kind	200	
Rock, equal to ashlar masonry	25	30
Brick, equal to ashlar masonry	15	20
Brick, of poor quality	4	7
Clay in thick beds, always dry	4	6
Clay in thick beds, moderately dry	2	4
Clay, soft	1	2
Gravel and coarse sand	8	10
Sand, fine and compact	4	6
Sand, clean and dry	2	4
Alluvial soils and uncertain sand	0.5	1

[1] From "Treatise on Masonry Construction," by Baker.

NOTE. A complete bibliography on the subject of "Bearing Value of Soils" is contained in the *Proceedings of the American Society of Civil Engineers* for August, 1917.

For the machinery foundations, it is considered good practice to use somewhat lower values. About one-half is a good working basis for such work, thus allowing a maximum load of about 1000 pounds per square foot for ordinary alluvial soils. Clean, sharp sand is considered to be a good bearing soil; it may only be necessary to cover it with a concrete mat, which requires a minimum of concrete. For soft or alluvial soils, piling is almost always required. The piles may be of wood, although in the last few years much use has been made of concrete piles, both plain and reinforced. Such piles are less apt to decay, and their bearing power is higher, because of their greater friction. They may also be made of larger diameters than can be obtained with wood piles, and a smaller number is therefore required to support a given load.

When designing foundations, the first step is to ascertain the total weight that will be sustained by the soil and then to provide a sufficient number of square feet of area of the base to bring the pressure per square foot within the safe value. The weight should include the machines, fittings, the weight of the foundation itself, and, in the case of the turbines, the weight due to the water thrust, unless this is

balanced. Separate foundations should be provided for the different units, so as to isolate any failure as far as possible.

Concrete is always used for the foundations. They should be solid for the machinery, while the building may be supported on columns or arches so as to economize on the concrete. Where there is danger of high water in the tailrace, the outside foundation walls should necessarily be made water-tight, so as to prevent water from entering and flooding the basement. For such cases a sump is, therefore, generally provided into which the seepage may collect and whence it can readily be pumped out. A mixture of one part cement, three parts sand and six parts gravel or broken stone forms a concrete which is extensively used, and which has given perfect satisfaction for machine foundations.

On small machines, the foundation bolts and plates may be placed in position before the concrete is put in. They should be hung in place by a wooden template, and the bolts surrounded by stove pipe, conveyor pipe, or scrap-iron pipe, several inches larger than the bolts themselves. This allows for mistakes in location and variation in the machine parts, the holes being filled when the base is grouted. With large machines, however, it is better to have pockets in the concrete, large enough for the foundation plates to be dropped in. When these holes are filled in, and the base is grouted, they serve the further purpose of making a good bond between the foundation proper and the grout in and under the base.

The best grout mixture is half sharp, clean sand and half cement. It should be thin enough to flow readily and should be well puddled into place. Before pouring, all dust and trash should be cleaned off and the foundation thoroughly wet down. It is better to use a fairly slow-setting cement on large castings. In some cases, cement for grouting has been set aside and aged a year before using. Fresh or quick-setting cement may heat enough while setting to cause expansion and distortion of large castings. A record of the grout and room temperature should be taken as a check.

Floors. No combustible material of any kind should, if possible, be used in the construction of a power-house. As the substructure of the building is generally built of concrete, it is but natural that the floors should also be of concrete. A dark color is preferable, so as to render drops of oil inconspicuous. Tile or mosaic is possibly the best floor finish for a generating room. It is smooth, easy to keep clean, and has a very handsome appearance if made to conform with the general interior finish of the station.

Walls. The walls may be either of reinforced concrete construction or of brick with a steel skeleton framework. Where future extensions

are contemplated a false wall is provided on one end of the building. The interior should be kept as light as possible, and it is therefore advisable to apply a smooth surface of cement plaster and whitewash, or paint the same. For more important stations, the walls may be faced with pressed brick, enameled brick being used for about 10 feet above the floor. Where the extra expense is warranted, the walls may be entirely lined with enameled brick and a wainscoting of contrasting color, preferably olive-green.

Roof. The roof of the building should always be supported on the steel trusses, carried on the side of the walls or on the steel columns. The slope should not be excessive, 2 inches per foot being sufficient with gravel covering. This construction requires less material, and is advantageous when the transmission wires are to enter the station through roof entrance bushings, or where the lightning arrester horns are to be installed on the roof.

The roof covering may simply consist of boards covered with roofing paper, tar and gravel. Reinforced concrete is sometimes used in place of boards, so as to make an absolutely fireproof construction. Roofs covered with red tile are often used and present a very pleasing appearance. Corrugated iron roofs are objectionable, however, as moisture is liable to condense on the inner surface and drip into the station. They may also cause the station to be extremely hot in the summer, unless an insulating lining is provided below the roof trusses to keep out the heat. As this is also objectionable, corrugated iron roofs are seldom used for power-houses. With tile or metal roofs it is necessary to provide steeper inclines than with gravel roofs, so that the water may run off rapidly. The height of the trusses should be about one-third of the span. Monitors are sometimes provided so as to give additional ventilating facilities.

Roof trusses with a raised chord are in many instances of great advantage, in that they provide an increased headroom without unnecessarily raising the walls of the building. This is of special importance in the high-tension part of the station, where ample headroom must be provided for the busbars.

Windows. Good lighting is imperative, and large windows are therefore essential. They should be symmetrically located with regard to the generating units, and their design should be such as to harmonize with the building, arched windows being very generally used. Skylights of glass tile, placed in the roof, will also add considerably to the lighting. The window sashes should preferably be metallic and the glass reinforced with wire netting, so as to prevent shattering when broken. Ribbed or non-transparent glass is also desirable, because it

keeps out the intense rays of the sun. In order to provide for ventilation, the windows should be easy to open; in large stations they are operated by electric motors controlled from the main switchboard. Precautions should also be taken to prevent rain, snow and dust from blowing in on the machinery or apparatus. This is especially important on the switchboard side, where the wiring is exposed; and it is, therefore, better practice not to provide any means for opening the windows on that side. For tropical climates, all windows which are liable to be opened should be equipped with mosquito screens.

Doors. The location of the doors is naturally governed by local conditions. One of the openings should be of a sufficient size to admit a railroad car, and tracks should also be provided. Very often these doors are of the rolling type, this design being most economical as regards space.

Traveling Crane. Provision should always be made for supporting the track for a traveling crane, which should span the generator room and run the full length of the station. The track is generally supported on pilasters in the outside wall and on the steel columns separating the generator and switch rooms. There should be ample headroom allowed so that the various machine parts can be readily removed when repairs are to be made. This is especially important with vertical units, where the water-wheel rotor is mounted on the same shaft as the generator field, in which case it should be possible to lift out the whole revolving element by simply removing the top bracket and bearing of the generator.

The type of crane depends largely on the size of the units, the weight of the heaviest pieces, and the number of units in the station. In small stations, a hand-operated crane may be ample, while very large stations will require two electrically operated cranes. A few stations have been equipped with a gantry type of crane just long enough to straddle the generators and high enough for the highest lift. This type deserves more careful consideration than it has had heretofore. The span is shorter and consequently lighter than an overhead crane. The building framework can be designed simply for the roof load, with a material reduction in the steel required.

The crane should be of sufficient capacity to lift the total revolving element of vertical wheels and generators, unless some special arrangement of jacks under the generator rim, or on the shaft, is provided. This support is necessary to relieve the thrust bearing, for inspection or repairs. Jacks or supporting blocks under the generator field rim are also of great assistance during the erection of vertical units.

The question of armature repairs should be considered when design-

ing the crane equipment. A few coils can be replaced in a vertical machine by removing two or more field poles. Extensive repairs are best handled by lifting the entire armature above the field rim and supporting it on substantial blocking. A temporary floor is laid on the top of the field spider for a working platform. This arrangement does not disturb the line-up of the revolving parts and usually makes a very material saving in time and expense.

Slings, lifting devices, hooks, equalizing yokes, etc., should be designed with ample safety factors and to allow safe, accurate and rapid assembly. Wire slings should be oiled to prevent rusting, and protected from kinking or cutting on sharp corners by pads or their equivalent. Angle pieces made from boiler plate are good, cheap and durable. Any slings that show wear or weakening should, of course, be replaced.

Ventilation. Particular attention must be given to the ventilating problem in the design of the building, especially for large installations where the heat to be carried away from the generators is very great. The neglect of this important feature in stations, otherwise well designed, has led to considerable trouble from overheating the machines; for if no provision is made for admitting fresh air, the air in the machine pit and in the space around the machine is used over and over again. Fresh cool air can be taken to the generator pit through ventilating ducts especially built for this purpose below the floor; from the pit the air is drawn up through the machine by the fanning action of the rotor, or forced circulation may be provided by motor-operated fans, the heated air escaping through openings in the roof. Both intake and exhaust openings should in such a case, of course, be protected against dirt, wind, floodwater, etc. Dampers may be installed in the ducts, for controlling the air; and with very large stations it may be desirable to sectionalize the ventilating system.

When the ventilating air for the machines is taken from the generator room, the maximum difference between the inside or room temperature and the outdoor temperature should not exceed 20° F. (11.1° C.) during hot weather, since the air leaving the machine naturally is considerably warmer than the room temperature. It is also important that the difference in height between the inlet and outlet openings of the station be as great as possible, to insure the maximum draft. The importance of this is obvious from Table XXXVII.

With forced or positive ventilating schemes, where a definite amount of outside air will pass through the machine, a temperature difference of 30° F. to 40° F. (16.7° C. to 22.7° C.) between the incoming and outgoing air is not excessive.

TABLE XXXVII

QUANTITY OF AIR IN CUBIC FEET DISCHARGED PER MINUTE THROUGH A VENTILATING DUCT OF 1 SQUARE FOOT IN CROSS-SECTIONAL AREA. DIFFERENCE IN TEMPERATURE OF AIR IN DUCT AND OUTSIDE—20° F.

Height of Vent. Duct in Feet.	Cubic Feet per Minute.
10	153
20	217
30	265
40	306
50	342
60	375

The subject of ventilation is covered more fully in the section on "Generators."

Illumination. In most power-houses, general or overhead illumination has been found to be a more satisfactory system than local or drop lighting. Lamps and reflectors are so arranged that all parts of the room are well lighted and objectionable shadows prevented.

A fairly high intensity of evenly distributed illumination is desirable, and at the same time freedom from glare is necessary. The R.L.M. Standard Dome reflector with bowl enameled Mazda C lamp, or the Glassteel diffuser with clear Mazda C lamp, will meet most of the requirements of the interior portions. The latter type is more desirable where a higher quality of illumination is sought.

The following detailed directions indicate the general illumination requirements for the different parts of the plant.

Generator Room: This is generally quite roomy and often has a high ceiling. With especially high machinery, attention should be paid to the spacing of the lighting units, in order to prevent shadows. An intensity of at least 5 foot-candles should be provided, to enable one to observe the operation of the machines at all times and to make any necessary repairs or adjustments without recourse to drop lamps. This intensity would be obtained by using 100-watt units on 10-foot centers or 200-watt units on 15-foot centers.

Turbine Room: In order to see clearly the control by which the flow of water into the turbines is regulated, from 3 to 4 foot-candles of general lighting should be sufficient. One hundred-watt R.L.M. Standard Dome units on 12-foot centers will give this intensity. In the substructure compartments, where the regulating machinery is located, sufficient light should be provided, in order that inspection and repairs

may be easily made. As the atmosphere is moisture laden, vapor-proof equipment is essential.

Transformer and Switch Room: In order to reduce the danger of accidental contact with the apparatus and the likelihood of mistakes in operating the switches, a reasonably high intensity of illumination (8 to 10 foot-candles) is especially desirable here. Whatever system of lighting is used, the units should be so spaced that the rear of the switch structures is well lighted, so as to permit inspection and repairs.

Control Room: The operator is constantly dependent upon his vision for the accurate reading of the dials and the successful manipulation of the switches, and must be supplied with proper lighting.

The glassteel diffuser, or similar equipment giving good diffusion, and thus reducing the likelihood of reflected images, is especially well suited for use in the control room. If a regular spacing of outlets is practical, 200 watt units on 10-foot centers will prove satisfactory.

Maintenance: A system of maintenance and cleaning of the lighting equipment should be provided, in order to get the maximum efficiency of illumination, for all units collect more or less dust and the lamps tend to become blackened.

Whenever possible, the walls and ceiling should be finished in light colors, as they not only reflect the light much better but give a clearer and more cheerful appearance to the room.

The power for the lighting should be taken from the auxiliary station service. As a protective measure, it is a good method to arrange about one-third of the lights, well distributed in the station, on a separate circuit, which, in case of trouble, may be switched over to a battery or other reserve source. In some stations this is accomplished automatically.

For illuminating outdoor equipments, flood-lighting has, of late, been used with very great success.

Heating. The heating of the power-house building is ordinarily, to a very great extent, done by the heat radiated from the machines, and an arrangement can be made whereby, during cold weather, the ventilating air may be used over and over again until it reaches a certain temperature. In many stations separate provision must be made for heating. In some cases this is done by means of electrical heaters, while in others complete steam-heating systems are installed. In connection with these, a steam-cleaning plant for waste, which necessarily is used in considerable quantities in large stations, can readily be provided.

Auxiliary Power Supply. In most hydro-electric power stations, the power for lighting and auxiliary service motors is taken from the

main bus through step-down transformers. In several recent installations, small water-wheel driven units, for supplying all or part of the auxiliary power, either for regular or emergency service, have been installed. In one particular case, duplicate auxiliary generating units are provided, feeding an auxiliary power bus which is not connected in any way with the main station bus. In another case, the auxiliary power bus is supplied by separate auxiliary water-wheel driven units and is connected to the rest of the system only by means of a transformer connection to the high-tension bus. The main idea in such cases is to free the main power circuits from the possibility of interruptions due to failures of equipment connected to the auxiliary power supply.

Another system, which would only be justified for very large stations, is that contemplated for the new extension of the Hydro-Electric Power Company at Niagara Falls. Each of these generating units, which will have a capacity of 65,000 kv.a., will be provided with a 650-kv.a. auxiliary generator mounted above the main unit and direct-connected to it. These individual auxiliary generators will then supply all the power needed for the auxiliaries of the generator to which it is connected, making each unit entirely independent of the others. In case of failure of the auxiliary generator, arrangements will be made for supplying power to the auxiliaries from an emergency circuit.

Miscellaneous. Provision should, of course, also be made for necessary repair shops, store rooms, offices, toilets, etc., and protective measures for accidents and fire must not be neglected. A vacuum compressed-air system may be required for cleaning or other purposes, and a complete water-supply system to various parts of the building is, of course, also necessary. Elevators and ample stairway facilities are essential, so as to permit a ready access to important points, as, for example, between the generator room and the switchboard gallery.

2. ARRANGEMENT OF APPARATUS

General Considerations. The arrangement of the apparatus should be very carefully considered from the standpoint of simplicity and reliability of operation. The purpose of the station being to give reliable service, consideration must also be given to the causes of disturbances and means for minimizing their effects. In anticipating these abnormal or so-called emergency conditions, the failure of every piece of apparatus must be considered as a possibility, and a definite plan worked out for limiting the magnitude and area of such disturbances.

In arranging the apparatus, the unit principle is often adapted, and to great advantage. Each main generator with its transformer is made a complete unit, in so far as operation is concerned. By carrying out this scheme it is possible to transmit the power from the generators to the outgoing transmission lines in the shortest possible distance.

Turbines. With horizontal sets, the turbines may be located, together with the generators, in the generator room, or in separate wheel chambers built in the dam or partition towards the forebay. The latter practice is only used for very low-head developments, where one of the power-house walls forms part of the dam structure. With vertical units, the turbines are always located in a substructure.

Governors. The governors are generally located on the generator room floor, close to the units which they are to control, and connected to the operating cylinders on the turbines directly below. The governor oil pumps, with their pressure and storage tanks, are installed in the basement, as is also the oiling system for the turbo-generator units.

In some of the latest installations, integral governors are used in which case the control mechanism is located immediately on the operating cylinders, thus forming an integral part of the turbine.

Generators. The main generating units are located on the main floor and are almost always arranged in a line along the long axis of the station (Fig. 94). They should be placed so far apart that ample space for passage is provided between them. Horizontal sets may be installed either at right angles (Fig. 95) or parallel (Fig. 96) to the long axis, the latter method being necessary for high heads where impulse wheels are used. The arrangement of the rest of the equipment, such as the transformers, may also be a determining factor in regard to the direction in which the sets should be installed. If one transformer bank, consisting of single-phase units, is to be installed for each generator, the space occupied by them may be of such a length that it would be more economical to install the turbo-generator sets parallel to the long axis, thus reducing the width of the building.

Exciters. Where common exciters are used, they are, as a rule, installed on the same floor as the main generators and in the center of the station. The advantage of such an arrangement is that the exciters will be located close to the operating switchboard, and the amount of copper required for the exciter leads is thus a minimum. The system may readily be sectionalized, one exciter serving the generators located in one-half of the station, and the other the generators on the opposite side. This does not, of course, refer to direct-connected exciters or to individual motor-driven exciters, which are located near their respective generators.

Transformers. Unless installed outdoors, the step-up transformers should be located on the main floor, on account of their weight. They are generally installed in isolated compartments in the rear bay, and these compartments should be sufficiently large to allow a good ventila-

Fig. 94.—Interior of Generating Station, Cedars Rapids Mfg. and Power Company.

tion. A car track is provided on the generator room floor in front of the transformer compartments, whose floors are raised so that the transformers can be run out on the car and moved to some convenient place in the station where repairs can be readily made. For large units it may be necessary to provide a hole in the floor above the repair room so as to enable the transformer core to be lifted out of the tank, or a pit

may be provided into which the transformer may be lowered so that sufficient headroom is obtained for lifting out the core. Sometimes the repair room is so situated that the main crane cannot be utilized for dismantling the units. In such a case a chainfall, supported from a heavy I-beam in the floor above, may be provided. This, however, as a rule, only refers to smaller plants.

The oil tanks should be located in the basement, and particular care should be taken to avoid any fire risk. For this reason it is advisable to install the tanks in separate enclosed compartments, and in certain

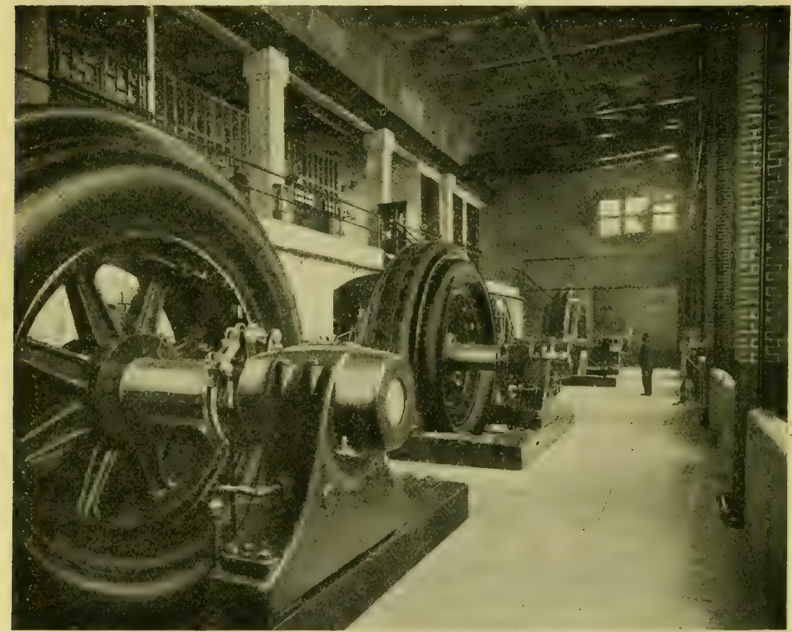


Fig. 95.—Interior View of Generating Station, Connecticut Power Company, Falls Village ~~River~~ Development.

cases these have been filled with sand. Their location should also be such that in case of fire the oil can readily be drained into the tailrace.

Current Limiting Reactors. As these are generally inserted between the low-tension bus sections, their location is in the low-tension switchroom. It is advisable to enclose them in compartments, like the transformers, and provision should be made for anchoring them securely. They should be installed at a distance of approximately half their diameter from any iron or steel structure, so as to prevent any heating of this and consequently increased losses.

Switchboards. The different pieces of apparatus comprising the switching equipment are distributed on the various floors in the sw section of the station, each story being partitioned to suit the var purposes. The operating room with the control switchboard is ge ally located on the second floor and in such a position that the opera or may have an unobstructed view of the station and be able to communicate readily with the turbine operators. A balcony, somewhat overhanging the generator room in front of the switchboard, is often pro-

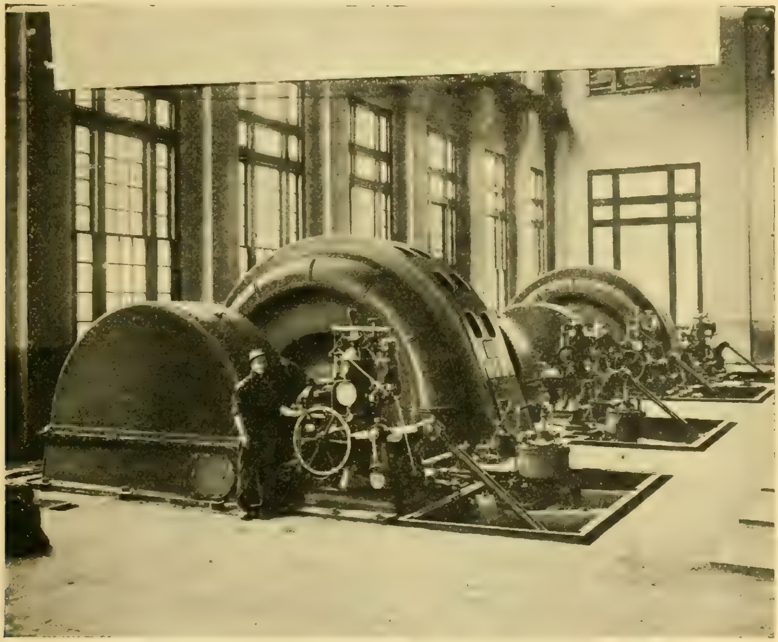


FIG. 96.—Interior View, Big Creek Development, Pacific Light and Power Company.

vided, or the operating room is built with a curved front wall extending out over the generator room.

The switchboard, containing the switches, etc., for the exciters and other station auxiliaries, should be located on the main floor at some convenient point, usually below the control-board gallery.

Oil Circuit Breakers. The low-tension oil circuit breakers are generally of the enclosed type and, together with the low-tension busbars, are located in compartments on the main floor back of the transformer compartments. The breakers themselves should preferably be set in parallel rows and opposite the generator and transformer bank which they control, so as to call for as short a connection as possible

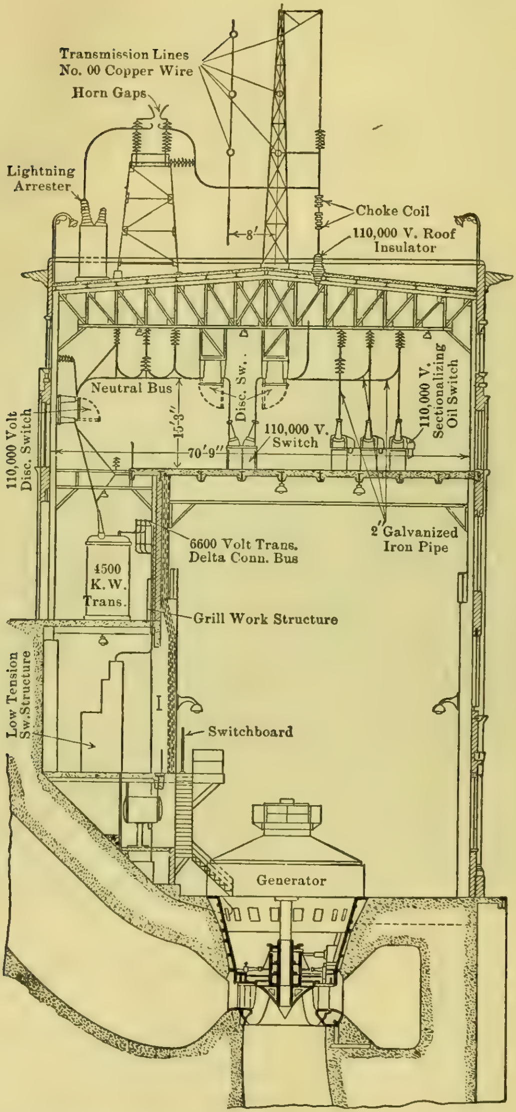


FIG. 97.—Power-house Arrangement. Alabama Traction, Light and Power Company. Lock No. 12 Development.

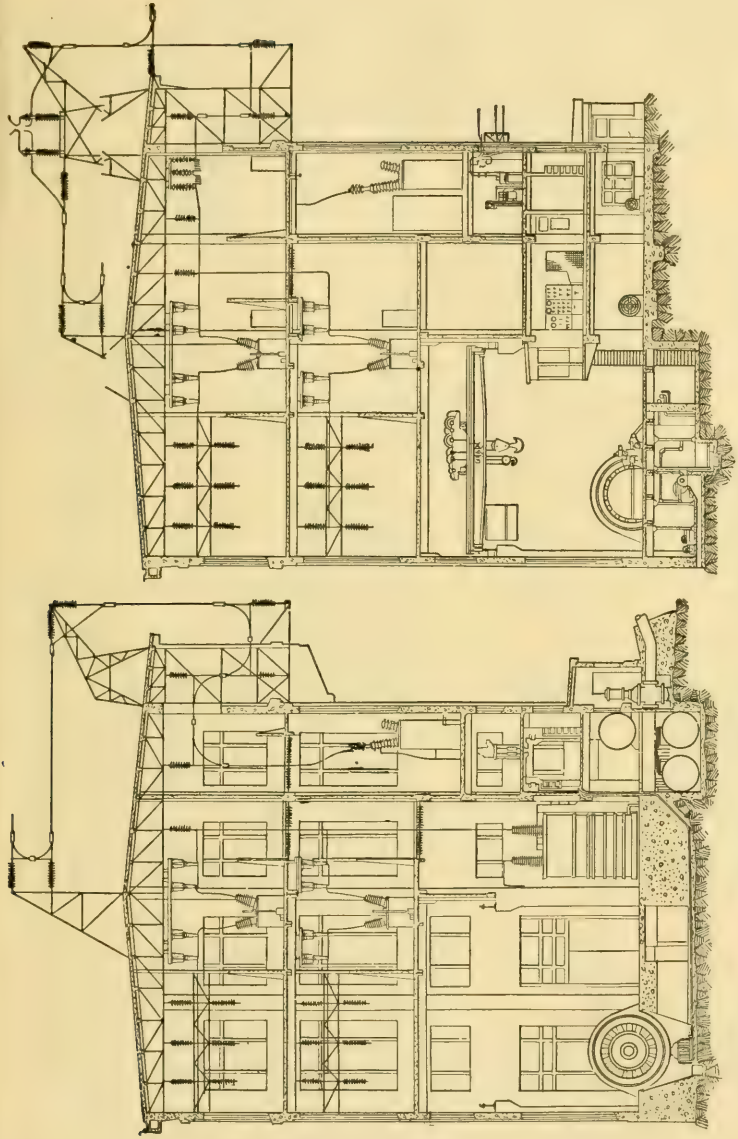


Fig. 98.—Sectional Elevations of Big Creek Power-house No. 1. Southern California Edison Company. (For floor plan see Fig. 98a).

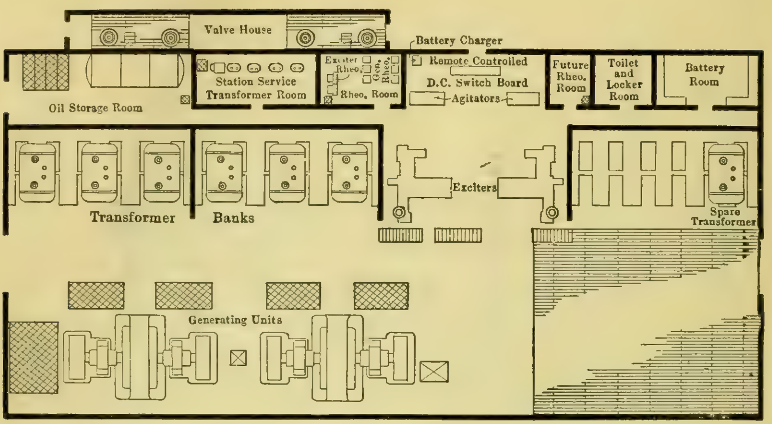


Fig. 98a.—Floor Plan of Big Creek Power-house No. 1. Southern California Edison Company. (For cross-section see Fig. 98.)

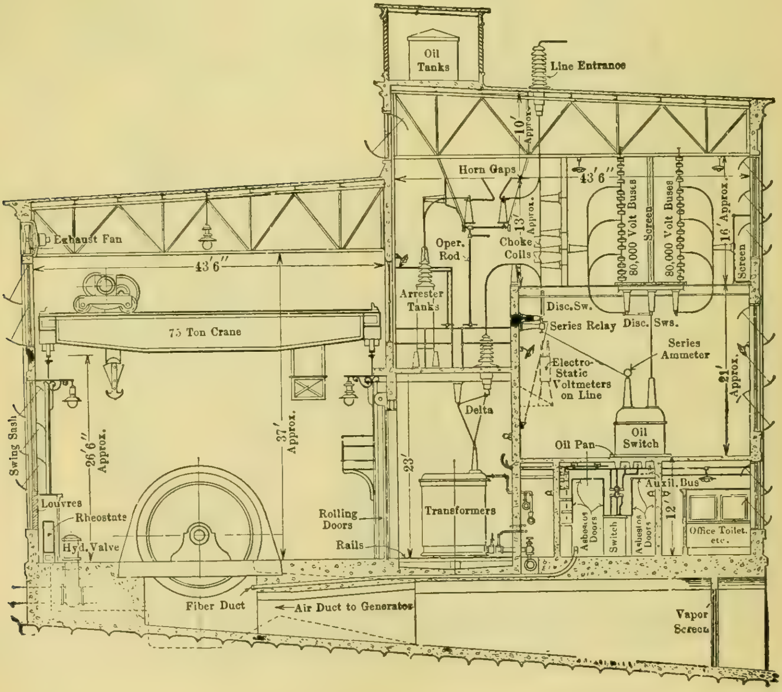


Fig. 99.—Typical Hydro-Electric Power-house Arrangement. Cross-section. (For floor plan see Fig. 99a.)

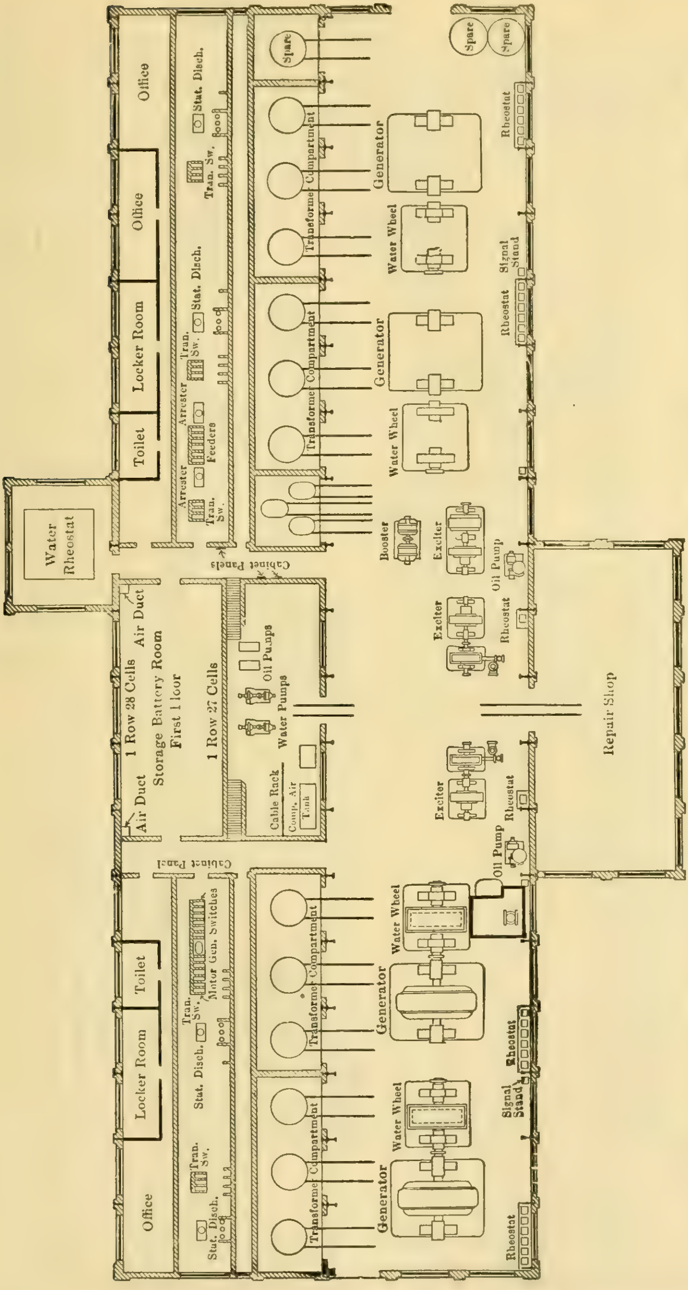


FIG. 99A.—Typical Hydro-Electric Power-house Arrangement. Main Floor Plan. (For cross-section see Fig. 99.)

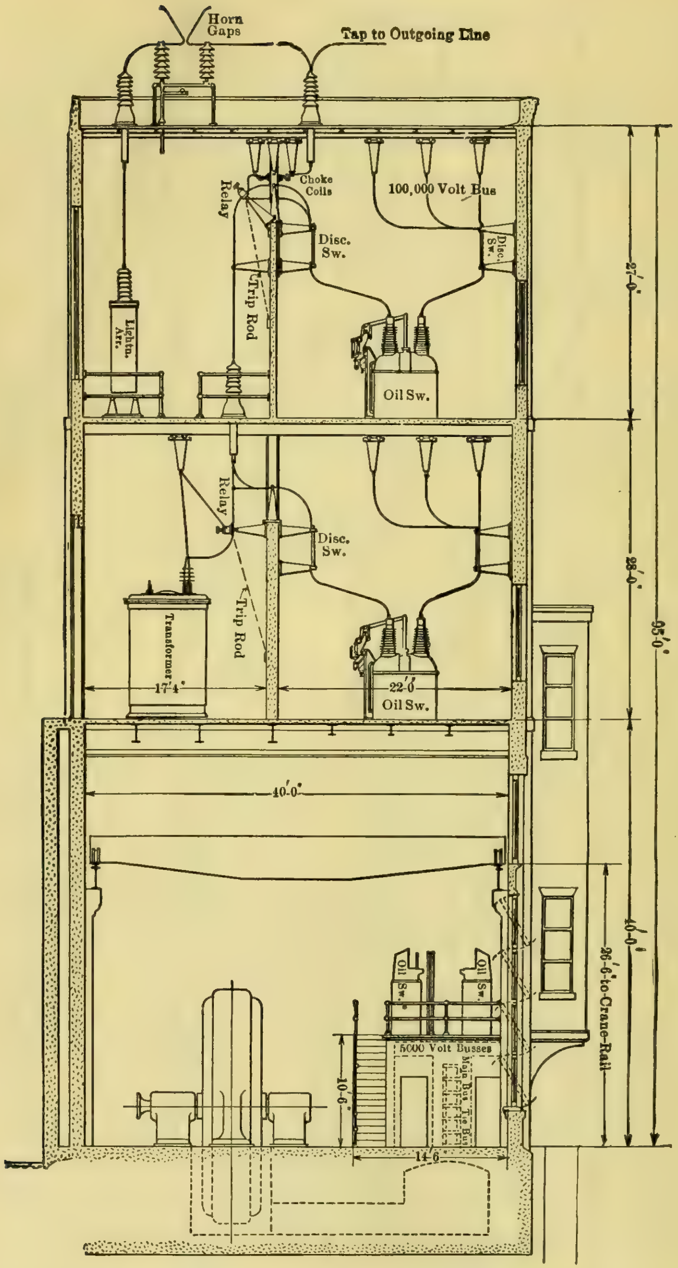


FIG. 100.—Sectional View of Hydro-Electric Power-house Arrangement with Limited Space. (For floor plans see Fig. 100A.)

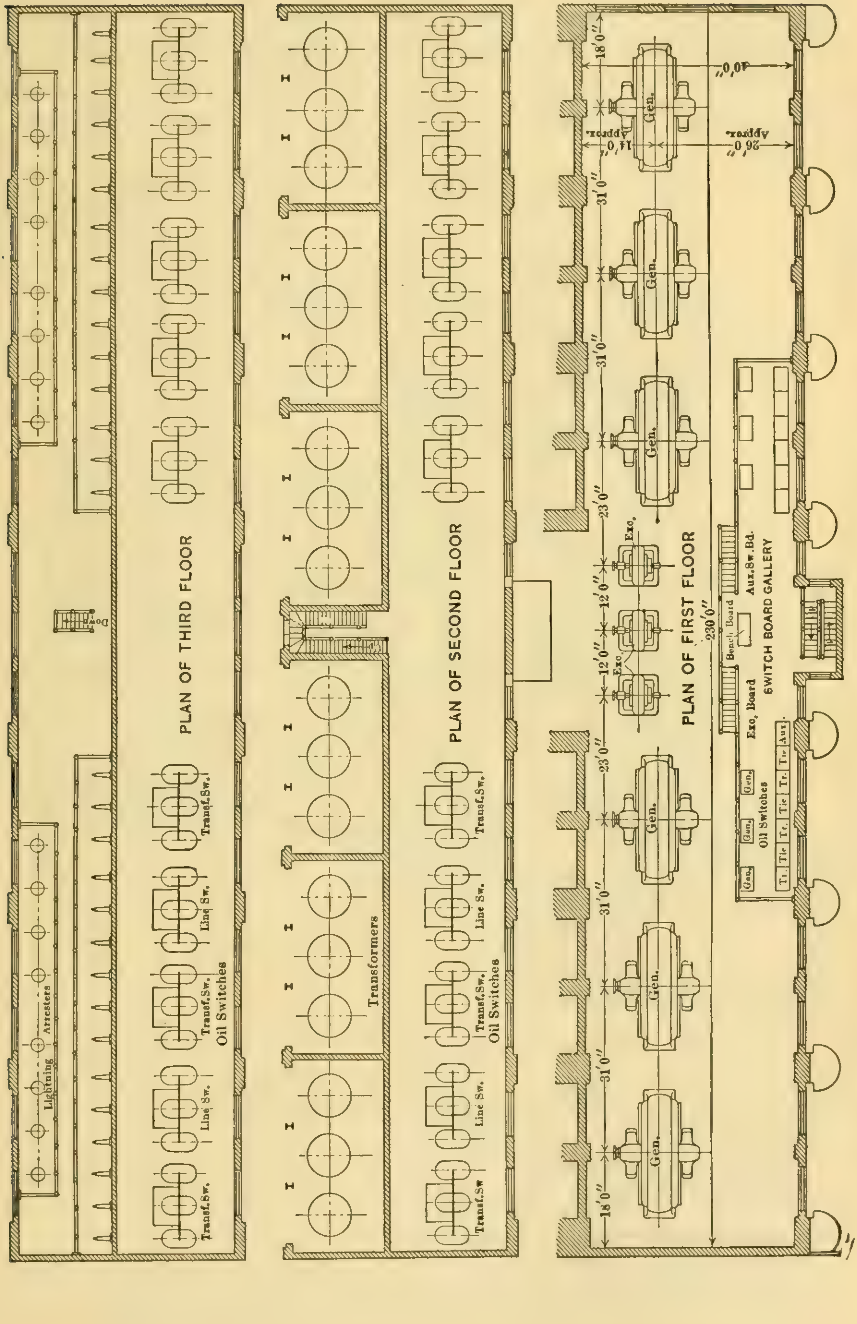


FIG. 100A.—Floor Plans of Hydro-Electric Power-house with Limited Space. (For cross-section see Fig. 100.)

and in order that these connections may be of equal length. The high-tension oil circuit breakers and busbars are installed on the floor above.

Lightning Arresters. The oxide film lightning arrester is now generally used with all new high-voltage stations. It may be installed either indoors or outdoors if the proper protecting hoods are provided.

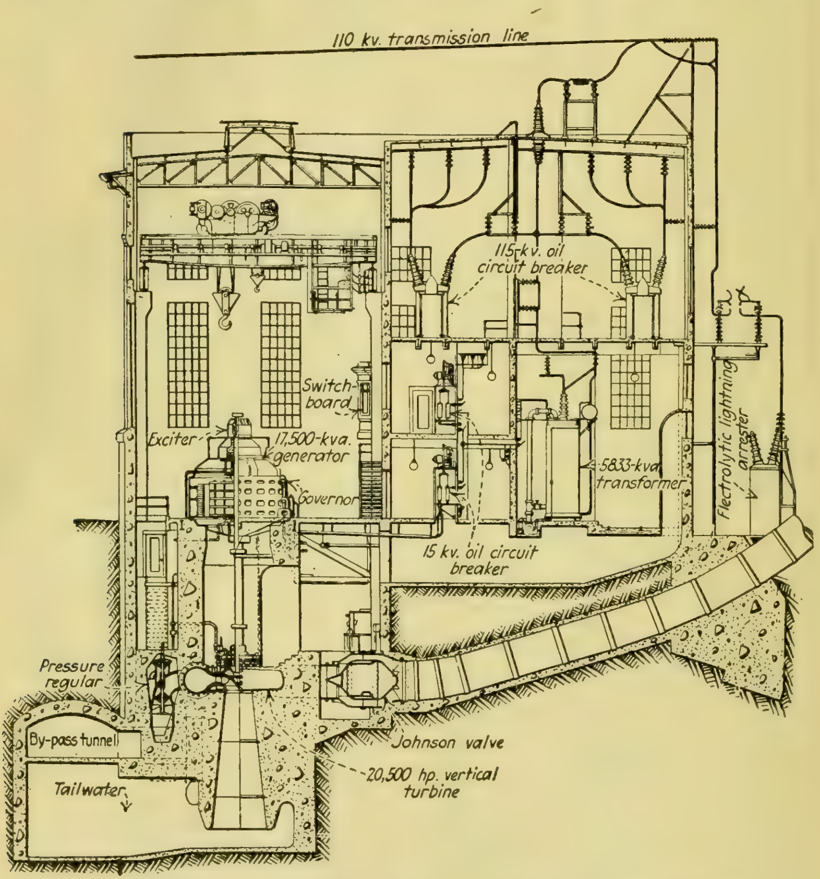


FIG. 101.—Cross-section Station No. 2, Los Angeles, Aqueduct System.

The arresters should be installed near the line entrances with short and direct line and ground connections.

Typical Station Layouts. A number of modern station layouts, illustrating some of the numerous ways in which the apparatus may be arranged are shown in Figs. 97 to 104.

Outdoor Stations. Now that the outdoor sub-station has been introduced and successfully operated, the practice of installing at least

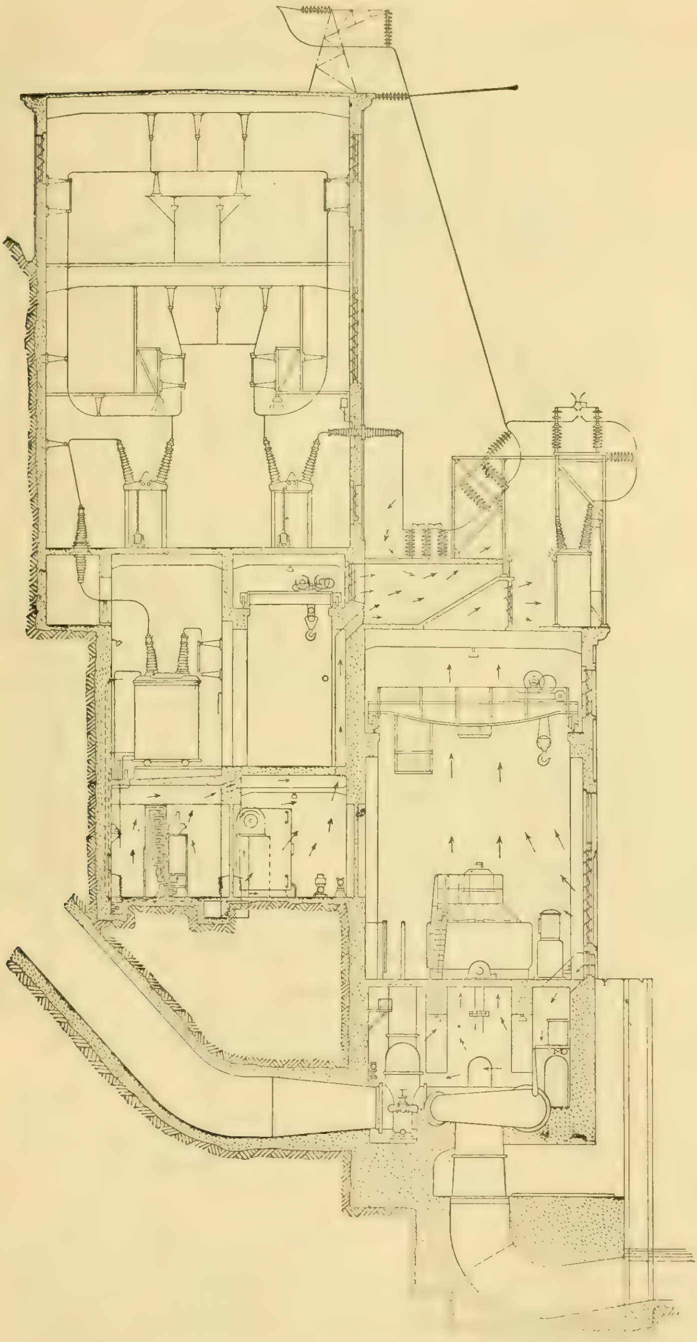


Fig. 102.—Cross-section of Generating Station, Ebro Irrigation and Power Company, Spain. (For plan view, see Fig. 102A.)

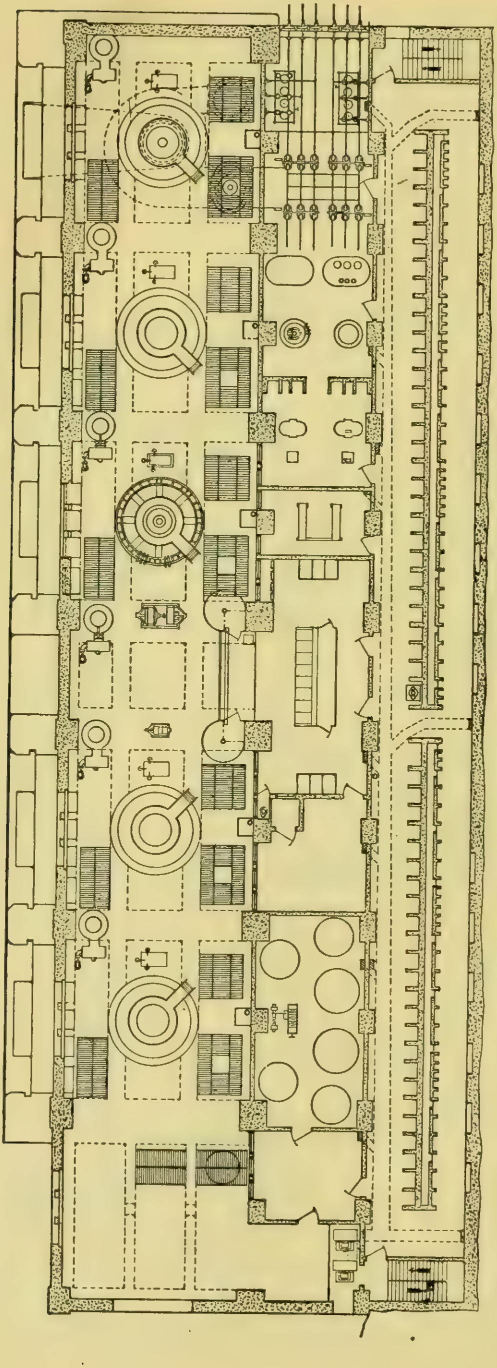


FIG. 102A.—Plan of Generating Station; Ebro Irrigation and Power Company, Spain. (For Cross-section, see Fig. 102.)

part of the generating station apparatus outdoors should be given careful consideration. It is entirely feasible to install the transformers and high-tension switching equipment outdoors, and such an arrangement will in many cases result in a considerable saving, on account of

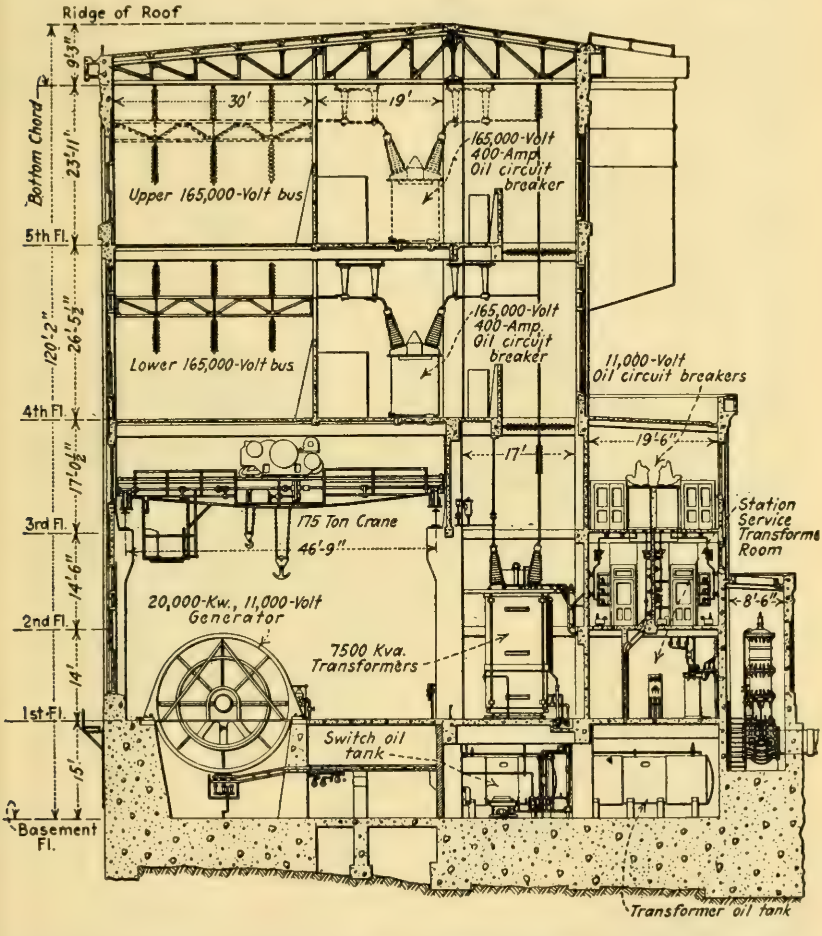


FIG. 103.—Sectional Elevation Caribou Power Station, Great Western Power Company. (For floor-plan, see Fig. 103A.)

the increasing size of such apparatus with higher voltages, and the high cost of housing them.

Little progress has been made, however, on outdoor installations of generating or other rotating equipments, although many proposals for such schemes have been made from time to time. Figures 105 and

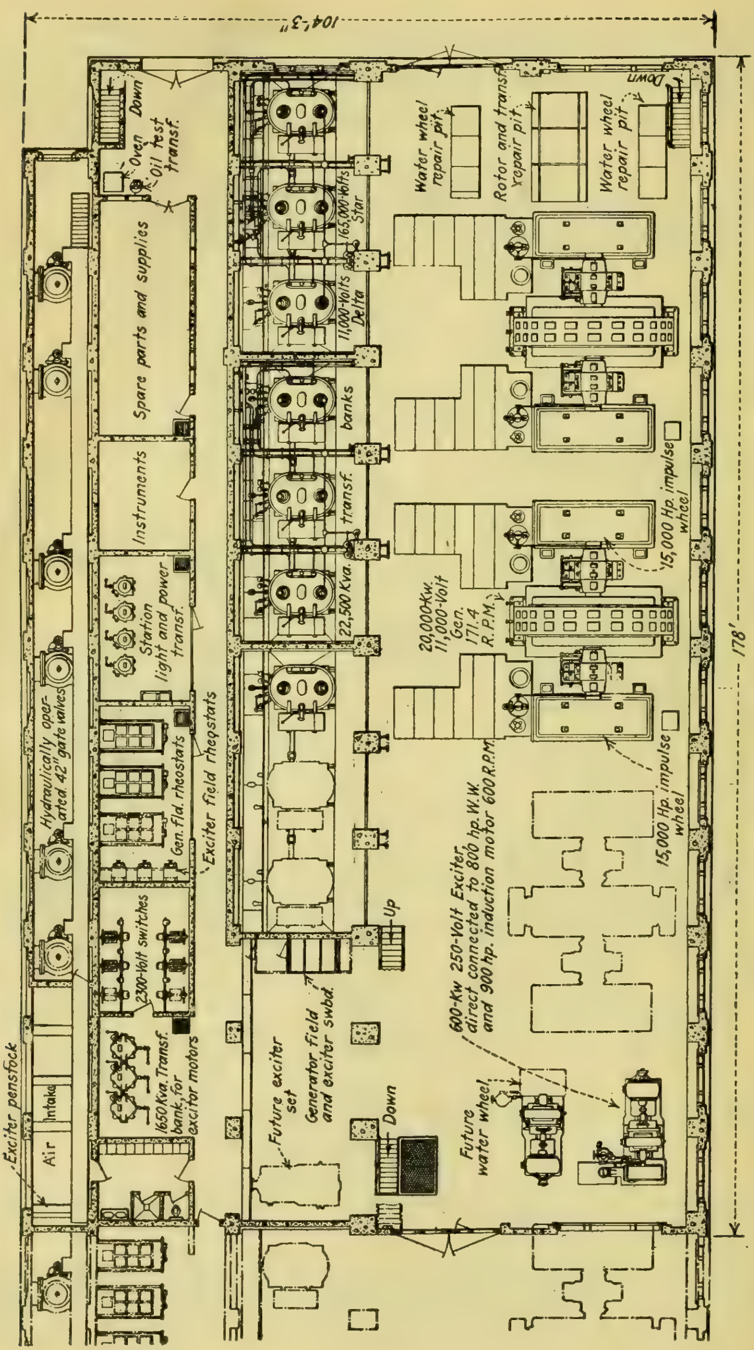


FIG. 103A.—Main Floor Plan, Caribou Power Station, Great Western Power Company. (For Cross-section, see Fig. 103.)

105A thus show the proposed outdoor arrangement for the Muscle Shoals Development in Alabama. This arrangement was not adopted, however, and the station is being constructed according to the indoor principle. This outdoor arrangement was proposed by Viele Blackwell & Buck, Consulting Engineers of New York.

Numerous outdoor transformers and high-tension switching equipments are now in very successful operation. The high-tension buses and connections, together with the disconnecting switches, choke coils,

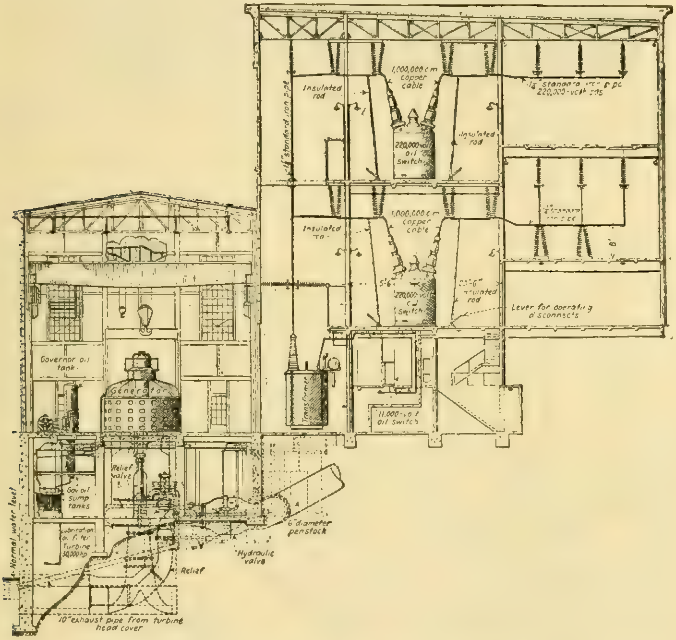


FIG. 104.—Section through Big Creek Generating Station No. 8. Southern California Edison Co. (220,000 Volts).

lightning-arrester horn gaps, etc., are generally mounted on steel structures or trusses supported on towers, the layout being governed by the equipment and the method of control which has been adopted. The line wires should be securely anchored before entering the station structure, and no unnecessary strains should be permitted in the wires inside the structure. Consideration should be given to deflections resulting from different pulls on the connections and also to unequal settlement of supporting towers, which may readily cause excessive stresses and insulator breakages, resulting in service interruptions.

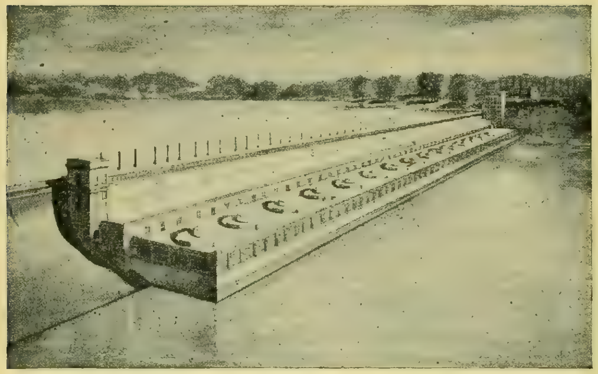


FIG. 105.—Outdoor Station Design Proposed for the Muscle Shoals Development in Alabama. (For Cross-section, see Fig. 105A.)

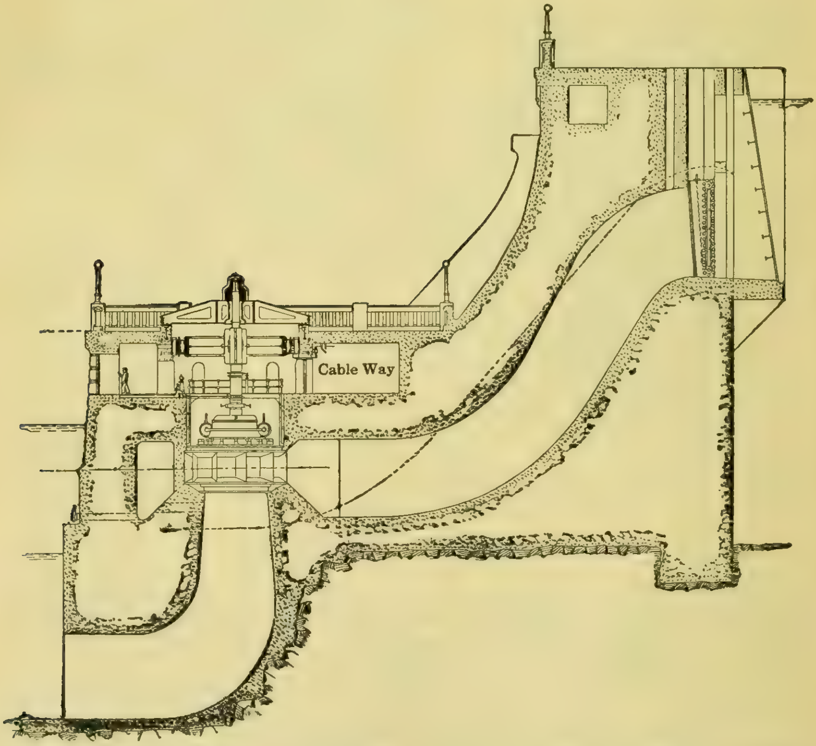


FIG. 105A.—Cross-section of a Generating Unit in the Outdoor Station Proposed for the Muscle Shoals Development in Alabama.

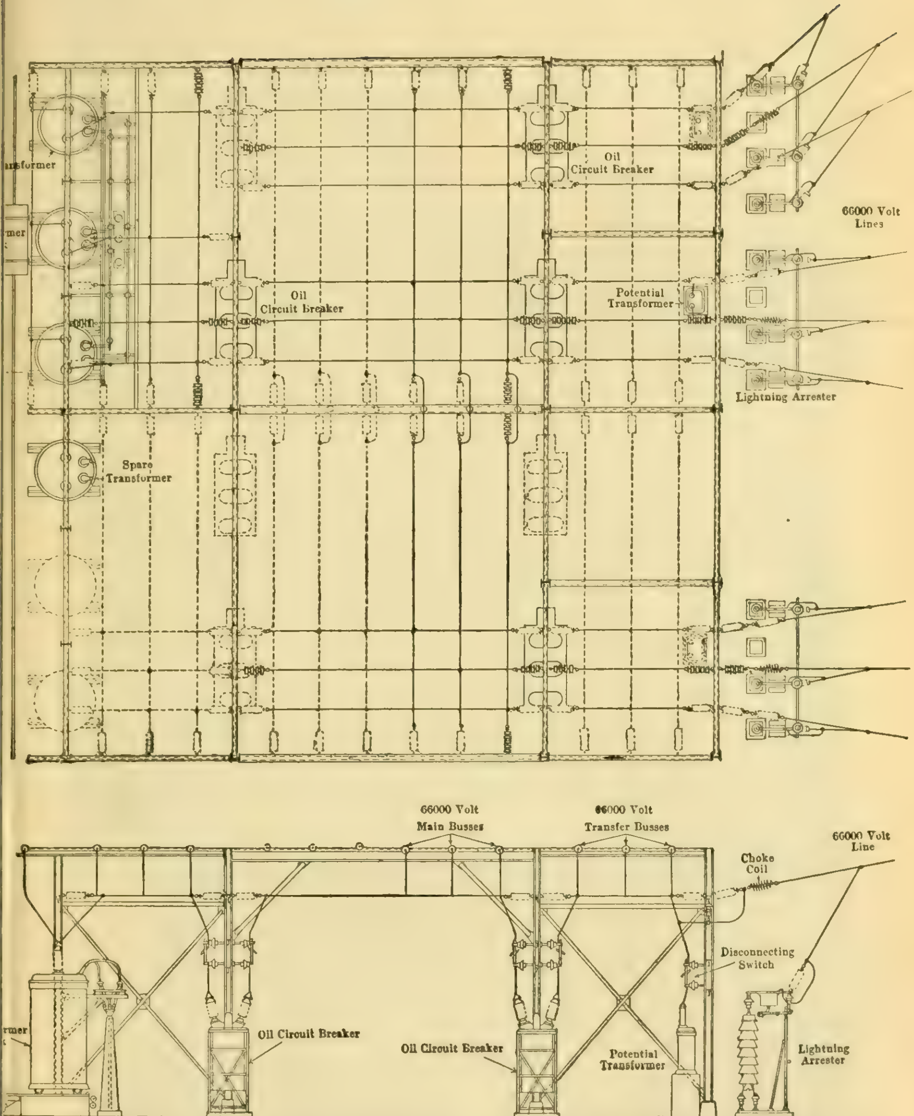


FIG. 106.—Typical 66,000 Volt Outdoor Transformer and Switching Station.

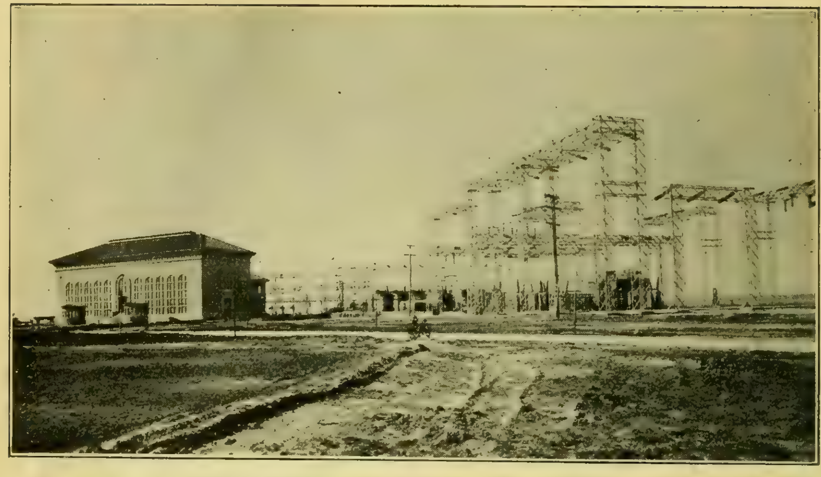


FIG. 107.—General View of Vaca Substation Pacific Gas and Electric Co.

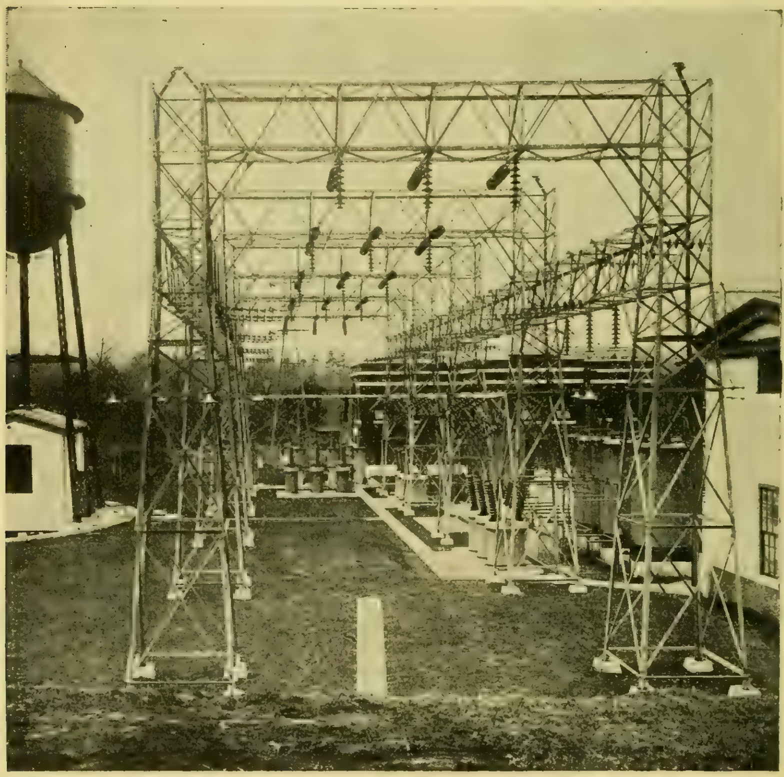


FIG. 108.—110,000-volt Outdoor Transformer and Switching Station.

The spacing of all the conductors, as well as that of apparatus, should be liberal but not unnecessarily large.

The oil circuit breakers and transformers are generally located on the ground, on concrete foundations of sufficient height to be clear of water; and the station should be well paved and drained around the apparatus. Transfer tracks with a truck will also be found very convenient when moving the apparatus. Cement walks should be laid on that portion of the ground where the operator is most apt to pass in

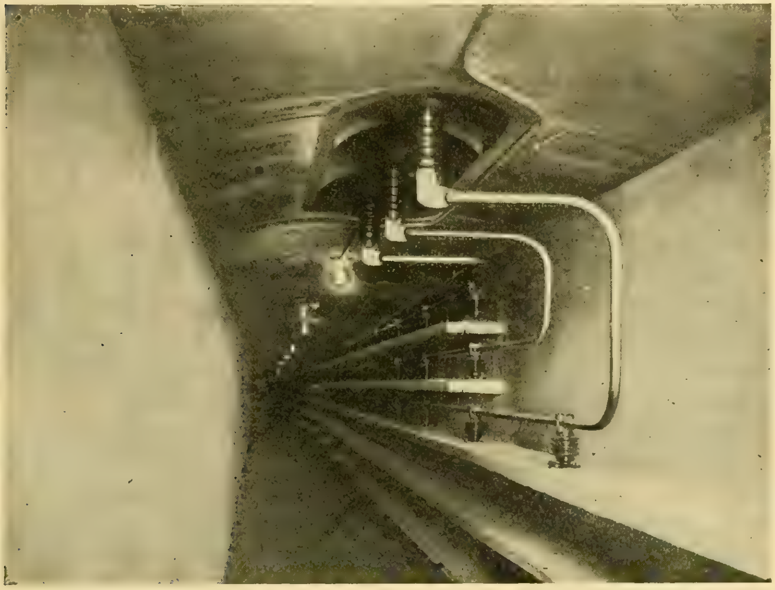


Fig. 109.—Showing Method of Bringing Low-tension Leads from Outdoor Transformers to Building through a Tunnel.

his inspection trips and work about the place. The oil piping to the transformers and switches, and the water piping, if water-cooled transformers are provided, should be so arranged that connections can be made or broken for any unit without disturbing the operation of the other.

Figures 106 to 108 illustrate typical outdoor arrangements, and Fig. 109 shows how the low-tension leads can be brought from the building through tunnels to the outdoor structure. The leads shown in the illustration come from the low-tension terminals of a transformer located above.

3. TRANSPORTATION AND ERECTION

Transportation. The transportation of such large machines as are generally involved in hydro-electric power stations requires a careful consideration of the limitations imposed by the railroads or carriers. It is furthermore evident that these points must be considered at the time when the machines are selected or designed.

The shipping limitations are the clearances (height and width) and the weight. The former are governed by tunnels, bridges, platforms, etc., and the latter by the carrying capacity of the bridges, as well as that of the cars. Both vary for different roads and even divisions or sections of the same road, and in many instances considerable advantages may be gained by detouring. For example, it may be found that the extra expense of dividing certain parts of a machine in sections may be so high that a considerable saving may be made by detouring the shipment over a route whose limitations are such that the parts can be built and shipped as one piece, even if the extra distance is quite great.

Special cars may occasonally be obtained which will facilitate the shipment of large machinery. These may be provided with pits in which part of the machines may be recessed, thus decreasing the overall height, or they may be of extra large carrying capacity.

Unloading. The question of unloading and transporting material and machine parts from the nearest point on the railroad should have careful consideration early in the design work. The dimensions of the largest and the weights of the heaviest pieces should be obtained from all companies interested. Also, one should know how these pieces will be boxed and shipped.

It is always preferable to deliver the machinery in the cars under the station crane. Unfortunately, this is often impossible or impracticable on account of the expense involved. Local conditions, however, usually determine the best arrangement for each installation. In each case careful consideration should be given to the job as a whole, and to all the material which must come in. Steel cranes, water wheels, generators, transformers, switchboard equipment, cable, piping, etc., must all be handled.

A carefully designed erection equipment, with the job as a whole in mind, will effect material savings, as various contractors will either pay for the use of this equipment or make corresponding reductions in the total price.

In difficult country, or far from the railroads, it may be necessary to arrange with the various manufacturers for shipment of machinery,

partially, or totally, knocked down. The increased price should, in such a case, be balanced against the transportation costs.

Car ferries, inclined railways with car skidways or heavy trucking equipment, whatever is decided on, had best remain under the direct supervision of the resident engineer or general superintendent, who can determine the best schedule for handling all of the material.

Apparatus Storage. In many cases, material must be delivered some time before it is needed, i.e., during the summer navigation, before the rainy season, while the ground is frozen, etc. The question of storage, therefore, needs careful consideration, as there usually is insufficient room in the power-house, especially before the building is completed.

The castings and rough machine parts may be stored in the open. A derrick for unloading and reloading will answer on small jobs. On large installations it may prove advantageous to install one of the main cranes or a forebay crane on a temporary track supported on timber framework over a skidway. Finished parts must be protected from the weather, fittings and small parts from sneak thieves.

Electrical apparatus must be stored in a dry place and kept above the freezing-point. The best arrangement is an electric heater which is large enough to keep the storage building above freezing and arranged so that the temperature will always be higher than that outside. Great care should be taken to prevent fires. In the majority of cases, a responsible watchman on duty at all times is the best insurance against fire and thieves.

Schedule of Erection. A careful schedule of the erection work should be made, to insure rapid, efficient work and prevent congestion. At least part of the building steel and the crane should be erected before any of the heavy machine parts are delivered. The delivery of water-wheel parts should be arranged for in the order required, and with sufficient time allowance to permit of the assembly work keeping step with the wheel-pit construction.

On large installations, space and equipment must be provided for the necessary assembly of the machine parts before they are placed in their final position. Any convenient open space under the crane, and centrally located in regard to the final location, will do for the wheel parts.

The generators must be protected from the weather and from the dirt, smoke and cement dust usually present during the building construction. In the case of large generators, it is often necessary to assemble the punchings and wind the armatures on the ground. This is best handled in a temporary house, under a crane. The roof can be made in sections, with eyebolts, to permit easy removal with the crane

and the handling of the armature sections. This temporary building will protect the machines from dirt, moisture and mechanical injury. The winders will also do more and better work when protected from the noise, confusion and dirt of the power-house under construction.

In most cases the coils must be warmed before using. Where this is necessary, convenient heating ovens should be made part of this temporary house. These ovens should contain wooden racks for holding the coils, and steam coils or electric heaters under the racks for supplying the heat. In general, the ovens should range from 150° F. to 200° F. and should be large enough to permit of coils being heated for several hours. A little care in arranging the ovens for the ready placing of cold and removing of hot coils will affect materially the speed and costs of the winding work. Some very large coils must be heated internally with current. Direct current is best for this purpose. Usually one of the exciter sets will be of the proper capacity; failing this, it may be necessary to secure an electrolytic generator of the proper capacity and drive this by motor or engine. Current is also needed for heating the coils in the split where the armatures are shipped in sections.

Crane Service. This is usually the cause of considerable friction between the various erectors; oftentimes one man will tie up the crane unnecessarily, simply to prevent some other gang from using it, although this action is delaying the job as a whole.

The general superintendent, or resident engineer, should allot the crane without fear or favor, considering the progress of the work as a whole, or else allot it to the various gangs for stated periods. In some cases, the scheme of allowing the wheel erector to use the crane in the mornings, and the generator erector in the afternoons has worked well. Both men can then plan their work ahead and avoid delays.

Protective Features. All electrical apparatus and finely finished parts of all machines must be protected from injury by water, dirt and falling material during the erection and until the power-house is roofed and glazed. In most cases, a liberal supply of tarpaulins will answer, although some cases warrant a temporary shelter of lumber and roofing paper.

Some fire-fighting equipment should be installed before the erection is started. Trash, excelsior, packing cases and skidding should be cleaned out promptly, as the fire danger is great under the best conditions. Competent watchmen should be in charge whenever the erectors are not working, to guard against fire, thieves and malicious mischief. This last is by no means a negligible item, as every large installation sooner or later shows damage, or attempted damage, of this character.

It is unsafe and almost foolhardy to start any machine while the

general construction is going on, without a thorough inspection just before turning over. There are numberless cases where these inspections have brought to light bolts, tools, rocks and miscellaneous metal that had no excuse for being anywhere near the machine. These pieces are always in the air gap or at some adjacent point where the motion of the magnetic field will draw them into the air gap.

Cooperation. A conference of all interested parties should be arranged before starting the erection, and the various steps of the erection should be discussed and settled. This is especially important in the wheel and generator erection, as the successful operation depends almost entirely on the careful line-up of these units. Arrangements should be made at this meeting for checking up the line-up of the various parts, as this is nearly always a loophole for future discussion.

In case of trouble there is always the tendency to place the blame on "the other fellow." This can be absolutely avoided by having all work checked by the wheel erector, the generator erector and the resident engineer or his authorized representative and all three signing a statement, in triplicate, each party keeping his copy. This should read somewhat as follows: "We agree that unit —— is on the longitudinal center line within —— mils. The cross center line within —— mils." On the proper elevation within —— mils, and is level within —— mils.

Where a two-piece shaft is used, insert a clause, "The water wheel coupling is true within —— mils, the rim is true within —— mils. The generator coupling face is true within —— mils, the rim within —— mils." Where it is impossible to test the couplings on the ground, this test can be made at the factories, and a statement furnished. These statements should be called for in placing the orders for the apparatus.

4. STARTING UP

General Precautions. Before the machines are started for the first time, they should be carefully inspected and guarded to prevent damage from tools or other foreign material which may have been carelessly or maliciously left where they will cause trouble. The machines should be blown out with compressed air to remove dust and dirt. The bearings should be flushed with kerosene or oil, and, if self-lubricated, filled with clean oil of the grade recommended by the machine manufacturers.

If the station is equipped with a central oiling system, all the piping should be flushed with oil and the oil carefully filtered before it is fed to the bearings. A temporary by-pass from the feed pipe to the returns at the generator will be of great assistance in cleaning and testing the oiling system. All piping should be examined and tested for leaks.

The electrical connections should be carefully inspected by men of known responsibility. Loose-bolted contacts, oil switches with no oil or insufficient oil in the pots, dinner pails stored on top of the oil pots or in the bus compartment are common sources of troubles.

After the machines are ready for operation, the switchboard instruments must be looked over and any necessary changes made in the wiring. The synchronizing devices must be checked very carefully. The majority of them are single phase, and it often happens that mistakes in connections cause incorrect indication on the meter. Different phases on the two machines may be connected to the synchronism indicator, or the phase rotation of the two machines may be different. The phase rotation must also be checked.

Drying Out.[1] Generators and exciters will need more or less drying out, depending on the amount of moisture they have absorbed. It is assumed that they have been protected from rain and leaking water from concrete forms. The only other way moisture can get into the machines is by sweating or condensation, due to the machines being colder than the surrounding air. This condition can be largely, if not altogether, avoided, by keeping the power-house at an even temperature. Where heating the whole building is impossible, and the humidity is high, the machines may be enclosed in a temporary shelter with steam or electric radiators. In winter weather the machines should be kept above the freezing-point. In most cases, however, it is impossible to prevent some condensation, and some drying is usually necessary.

An *alternator* may be dried out simply by driving the rotor at normal speed for several days by the prime mover. However, if excitation is applied in addition the process will be accelerated. In this case a generator not provided with temperature detectors should be run at normal speed with the armature windings short-circuited and with a field excitation sufficient to give approximately 110 per cent normal current in the armature winding. Alternators provided with imbedded temperature detectors in the windings can be run at normal speed with such a value of current in the short-circuited armature windings as will give a temperature measured by the temperature coil of approximately 75° C. The drying out should be continued until the insulation resistance becomes constant at a value about that given by the empirical formula below. When this stage has been reached, as a matter of assurance that the machine is safe for operation at line voltage, it should be run on open circuit at about 120 per cent normal voltage for five minutes, bringing up the voltage gradually. After the short-

[1] For transformer drying see section on "Transformers."

circuit run, the generator should be run for several hours at full voltage before any load is thrown on.

When drying a simple shunt exciter it should have its field opened and its armature short-circuited by a cable which will carry two or three times the normal armature current and which is also of sufficiently low resistance to constitute a "dead short-circuit." When a generator of standard design is driven at normal speed, under such conditions, the residual magnetism will cause a circulating current to flow in the armature, its value being a good working value for drying out. Should it be found that the residual magnetism will not cause sufficient current to flow, the shunt field should be very weakly excited from some external source (the low field current necessary can be obtained either from a very low-voltage source direct or from an ordinary voltage source by inserting a high resistance in the field circuit). If severe sparking takes place at the commutator when operating under these conditions, it can be minimized by giving the brushes a forward shift. Ordinarily, enough heated air will be thrown off the rotating armature to dry out the field. In case this proves to be insufficient, or only the field is damp, heat can be localized in the field winding while the machine is at rest by connecting the spools to an external source of excitation. Only a small current should be sent through the spools, so that the temperature of the spools will not exceed 70° C. by thermometer.

A commutating-pole machine that has no series-field winding should be dried out in the same manner as described for a simple shunt machine. See that the brushes are not back of the neutral but are slightly forward of it. The commutating-pole winding is to be wired in exact accordance with the standard diagram of connections for operation; and the short-circuit placed on the machine is to include the commutating-pole winding as well as the armature.

A compound machine should be dried out as described in the foregoing, except that the series-field winding should be cut out of circuit entirely. The latter is a precaution to prevent the possibility of the machine building up as a series generator in case no external excitation is applied to the shunt field.

Insulation Test. When the machine is dry and clean, the insulation resistance of the armature in megohms, in accordance with the A.I.E.E. Standardization Rules, should not be less than the voltage of the machine divided by the kilowatt rating plus 1000. That is, the insulation resistance in megohms should be equal to or greater than

$$\text{Resistance} = \frac{\text{Rated voltage}}{\text{Rated kw.} + 1000}.$$

Before power from any circuit is used for testing the insulation, it is necessary to ascertain whether the supply circuit is grounded. One side of the circuit must be free from grounds, and the ungrounded side should be used in series with the voltmeter in making resistance readings. Lack of care on this point may cause personal injury due to a short-circuit caused by attaching an ungrounded side of a grounded circuit to the frame of the machine.

Connect one side of a direct-current source of power to the windings to be tested; connect the other side of the direct-current circuit to a portable voltmeter; and then read the voltage when the free side of the meter is connected to the other side of the circuit where it is attached to the windings. Call this reading V. Then connect to the frame of the machine, being careful to get a good contact; call this reading V_1. Then

$$R=R_1\left(\frac{V}{V_1}-1\right),$$

where R = the cold resistance of the insulation, and

R_1 = the resistance of the voltmeter itself, this value usually being given inside the cover of the instrument.

Tets for Phase Rotation. Before an alternating current generator is operated in parallel with another generator, their respective phase rotations must be the same. To change the phase rotation of three-phase machines, any two of the three leads should be interchanged. With two-phase machines the two leads of either phase should be interchanged.

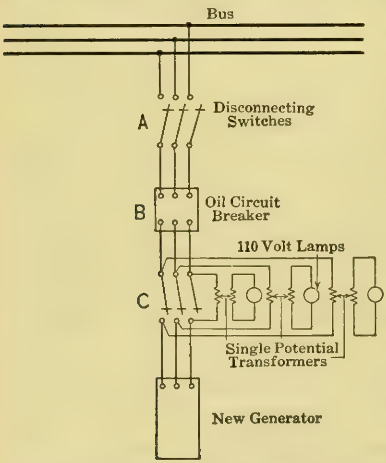


FIG. 110.—Connections for Testing Phase Rotation of A.C. Generators.

The phase rotation may be checked by connecting each alternator separately to an induction motor to see if the same rotation is obtained. A further test consists of connecting lamps between corresponding terminals of two generators, on all phases, through potential transformers. With connections as shown in Fig. 110, close disconnecting switches A and oil circuit breaker B. Leave switches C open. Then, by means of the field control of the alternator, apply sufficient voltage to make the lamps glow. Carbon lamps are best

suited for this test. If the phase rotation is correct, all the lamps will light up and go out together. If the phase rotation is incorrect, these lamps will light up and go out at different times.

The phase rotation of the second alternator may be compared with that of the first alternator by running the second alternator as a motor and the first machine as a generator, both machines starting from rest. If the second rotates in the same direction as the first alternator its phase rotation is correct.

Starting (Alternator Operating Singly)

1. See that all switches connecting the alternator to any load are open.
2. Cut in all of the field resistance.
3. Start the set and bring it up to speed.
4. Gradually cut out the field resistance until normal voltage is obtained.
5. Close the oil circuit breakers.

Starting (Alternator Operating in Parallel)

1. See that all switches connecting the incoming alternator to any load are open.
2. Cut in all field resistance.
3. Start the set and bring it up to speed under hand control of the waterwheel.
4. Close the field switch and gradually cut out the field resistance until the voltage of the incoming alternator is equal to that of the bus.
5. Vary the speed of the incoming alternator until the voltage of the alternator and bus are in phase.
6. When the voltage of the alternator and bus are of the same value and in phase, close the oil circuit breaker.
7. Adjust the speed of the alternator by means of the governor of the prime mover to make the alternator take its share of the load.

When starting after an accidental shutdown, it is unnecessary to wait for the set to come to rest. As soon as the switches are open, begin the regular order of starting operation.

Stopping

1. Adjust the governor until the wattmeter indicates a light load.
2. Cut in the field resistance until the ammeter indicates a low value of current.
3. Trip the oil circuit breaker.
4. Close the waterwheel gates.
5. When the alternator comes to rest, open the field switch.

Exciter with Rheostat in Generator Field. Unless the alternator is to be excited from a common bus, or exciters are to operate in parallel, it is the usual practice to omit the alternator field rheostat. When a rheostat is used in the alternator field, only the minimum amount of resistance should be cut in, so as to reduce the loss due to resistance and to keep the exciter voltage down, because the exciter has to make up for the voltage drop across the alternator field rheostat; there have been cases where the exciter was being overloaded because an unnecessarily large amount of resistance was cut in the alternator field rheostat. Some resistance may be necessary for stable operation and to prevent reversal of current on heavy overloads.

Parallel Operation of Exciters. In order that exciters may operate in parallel successfully, it is necessary that they have the same voltage characteristics, i.e., falling or rising equally with increasing load.

Shunt-wound exciters operate successfully in parallel, because their voltage drops off with increase in load, the division of load being controlled by the respective field rheostat. When paralleling compound-wound exciters, a connection is made from a point between the series and commutating field on one exciter to a similar point on the other machine through the equalizer.

The exciters must have the same compounding, and the currents in the series-field circuits must be proportional to the kilowatt ratings of the respective exciters, so that the voltage of each exciter will move on its compounding curve an equal amount. This requires that the resistances of the series fields and leads between the equalizer and the line shall be inversely proportional to the ratings. For this reason it is often necessary to introduce extra resistance in some of the leads. The resistance of the equalizer must be low, not over one-fourth of the combined resistance of the series field and leads of one exciter.

A forward shift of the brushes on exciters operating in parallel increases the stability of operation. This has the additional advantage of insuring a drooping voltage characteristic at lower voltages.

When exciters to be paralleled are controlled by a voltage regulator, there is another point to be considered for successful parallel operation. The regulator controls the voltage by rapidly cutting in and cutting out resistance in the shunt-field circuit. The full field voltage of one exciter may be higher than that of the other exciters, and it may build up quicker when its rheostat is short-circuited. Assuming that the field rheostats of the two exciters are set so that with the regulator contacts open the voltages are equal, the more sluggish exciter will tend to maintain its voltage at a lower point than the more active one. The contacts, of course, open and close at the same speed on both. The

more active exciter would, therefore, tend to take more than its share of the load. To cause proper division, the resistance in the field circuit of the more active machine should be increased. When an exciter requires more than one relay, the resistance of its field rheostat is divided between the relays, and a change in position of the movable arm would unbalance the load on the different contacts. Therefore an external resistance, called the equalizing rheostat, is provided and inserted in the field circuit of the more active exciter.

CHAPTER VII

HYDRAULIC EQUIPMENT

1. TURBINES

Modern turbines may be divided into two classes: reaction turbines and impulse wheels.

Reaction Turbines. This type is a combined potential and kinetic energy wheel, or more properly speaking a turbine, since it admits water all around the periphery of the runner and all parts of the same perform useful work. The water enters the runner at a speed which is lower than the spouting velocity, and the pressure continues to drop throughout the runner. When operating, the turbine is completely filled with water, the channels acting as closed conduits running full.

The water may pass radially either inward or outward; or it may enter the runner radially toward the shaft and leave in an axial direction, i.e., in a direction parallel with the shaft. In this case the turbine is of the mixed-flow type, the type most extensively used in this country.

The speed of a reaction turbine can be varied not only by variation of the runner diameter but also, and very effectively, by varying the bucket angle and the angle between the entrance speed and the peripheral speed.

Three different designs for Francis reaction turbine runners are shown in Figs. 111, 112, and 113. The first, Fig. 111, represents a low-speed runner which would be used for relatively high heads and relatively small quantities of water. The bucket angle β is close to 90° and the angle α of the water leaving the guides is small.

Figure 112 represents a medium-speed runner, the angle β being approximately 90° and the angle α larger than in the previous type.

Figure 113 represents a high-speed runner for low heads and relatively large quantities of water. It is seen that the angle β is larger than 90° and the angle α also larger than before, thus giving a very high peripheral velocity.

Figure 114 represents a very high-speed runner of the so-called propeller type, the angle β being much larger than 90° and the angle α also considerably larger than before.

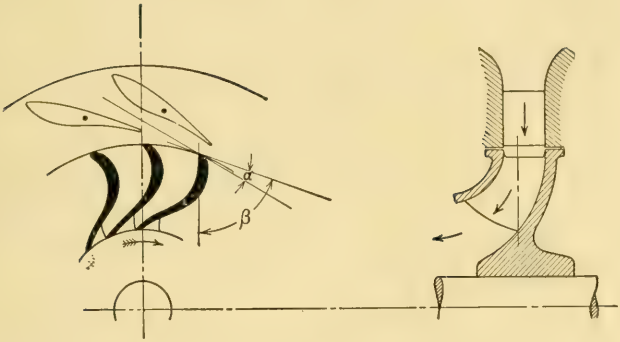


FIG. 111.—Low-speed Runner, Francis Type.

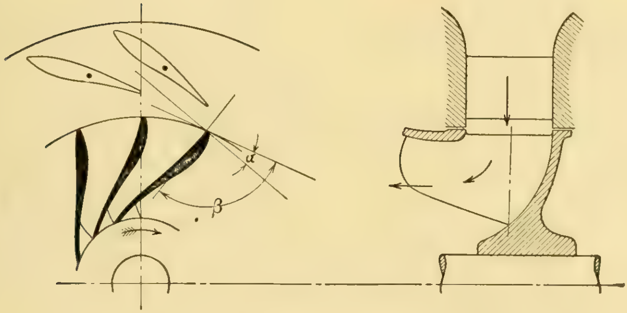


FIG. 112.—Medium-speed Runner, Francis Type.

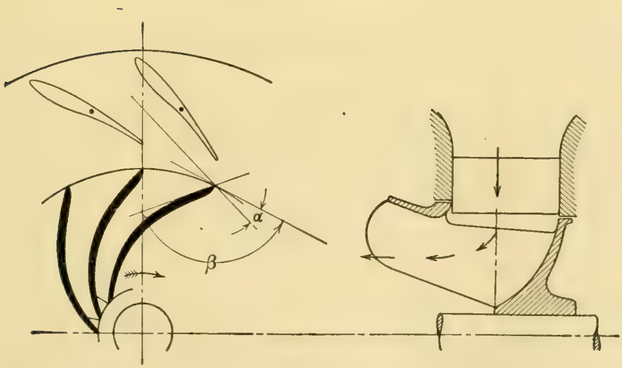


FIG. 113.—High-speed Runner, Francis Type.

Impulse Turbines. The impulse, or tangential, turbine is generally known as the Pelton turbine. It is a kinetic energy wheel, the water being discharged from one or more nozzles against a number of buckets attached to the periphery of the runner, and the momentum of the mass of water in its impulse upon the runner buckets is, therefore, the main principle utilized in the energy transformation. When the water leaves the buckets it is moving at so slow an absolute velocity that practically its entire energy has been imparted to the runner.

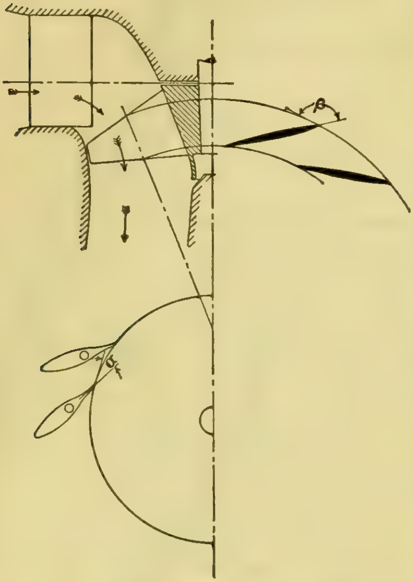


FIG. 114.—Very High-speed Runner, Propeller Type.

Since the number of nozzles is usually small as compared with the number of buckets, the latter are in active use during only part of a revolution, and hence this type of prime mover is sometimes called a water wheel instead of a turbine. This distinction seems, however, rather arbitrary, and can probably be traced to an attempt to show that the impulse turbine is derived from an undershot water wheel. It seems, therefore, better to consider both types as turbines, since they both really involve the same principles and action. As a matter of fact, the term water wheel is loosely applied to all sorts of turbines.

The description of the tangential type of impulse turbine is given on page 238.

The speed of an impulse turbine of a given diameter is variable only within very small limits. The speed is practically determined by the head, and can be varied only by variation of the runner diameter.

Selection of Turbines. In deciding upon the number, capacity and speed of the units in a water-power station, the combination of the turbine and the generator must necessarily be considered together. Besides hydraulic conditions such as the head and its variations, stream flow, storage facilities, etc., and the limitations of the turbine design, a proper selection is governed by the load factor, the nature of the load, the reserve capacity, the reliability and flexibility of the

service, the cost and operating expenses, etc. The units should be operated as near full load as possible, and new units should preferably be started as the load increases, instead of utilizing overload capacities. Where sudden overloads of considerable magnitude come on the system for short periods, it is, of course, necessary to have turbine capacity sufficient to care for them. Single units are never desirable except for multiple-plant systems, in which case the necessary reserve can be obtained from other stations. For single-plant systems the number of units should preferably not be less than three or four; if more are necessary the number should be governed by the upper limit in design, considered both from a technical and economical standpoint. With a small number of large units, the first cost, the maintenance charge and the necessary floor space is reduced, and the efficiency is also usually better than for a larger number of smaller units. The ultimate development may also influence the size, and it may be found advisable to provide larger units for the initial development than would otherwise have been chosen.

As, in most cases, the factor of cost influences the number and size of units, it is important to compare the cost of several different combinations in order that the special features arising in each case and their importance may be definitely ascertained as a preliminary to the final working out of the problem. It is usually considered preferable to have units of the same size in each station.

Many water-power developments are subject to wide variations in the head, and the backwater may bring about a change in head, which will very materially reduce the capacity of the turbines. For such emergency conditions, it may be necessary to provide reserve units which can be thrown into service at such times. There are, of course, other means to minimize the effect of high backwater, such as the Thurlow backwater suppressor, described on page 82 and the Moody Ejector turbine. In the latter, at low heads, a jet of water at high velocity is allowed to enter the draft tube without first passing through the runner; the jet simply creates an additional suction head, which compensates for the loss in the difference in level between the head and tailwater. In this connection, it might also be stated that the characteristics of the propeller type turbine are such as to make it much superior to other types for conditions where the operating head is likely to vary.

Specific Speed. Turbine runners of different makes are best compared on the basis of their specific speeds, this being the number of revolutions per minute, at the point of maximum efficiency, that a homologous or geometrically similar wheel would give if it were to

deliver 1 horse-power under unit head, usually 1 foot. With the same specific speeds, the different designs vary comparatively little, it being the aim of manufacturers to produce a line of turbines covering all specific speeds with the highest efficiencies possible at each specific speed; and turbines for use under low leads should have as high a specific speed as possible without sacrificing efficiency or other desirable characteristics. After a certain design has been adopted for a certain specific speed, a full series of such turbines can be laid out, all of identical design with the original, each being an enlargement or reduction of another.

If Q = quantity of water;
h = head;
D = diameter of runner;

then for any given turbine:

Q varies as $h^{1/2}$;
H.P. varies as $Q \times h$ or $h^{3/2}$;
R.P.M. varies as $h^{1/2}$.

Hence, the horse-power delivered under 1 foot-head will be

$$HP_1 = \frac{\text{H.P.}}{h^{3/2}}$$

and the speed will be

$$\text{R.P.M.}_1 = \frac{\text{R.P.M.}}{h^{1/2}}.$$

If now the head is kept constant and it is assumed that all dimensions of the runner are reduced proportionally, then the dimensions will all remain in fixed ratio to the diameter, D, and all areas of passages through the runner will vary in proportion to D^2; the velocities remaining constant on account of the constant head.

Therefore, for turbines of homologous or geometrically similar design, but built in various sizes and operated under the same head:

Q varies as D^2;
H.P. varies as D^2;
R.P.M. varies as $\frac{1}{D}$.

Hence, the speeds of a set of similar runners, operating under the same head, will vary inversely as the square roots of their horse-powers, and if one runner gives a speed of R.P.M. with a power H.P., it follows that the speed of a 1 H.P. turbine will be R.P.M. $\times \sqrt{\text{H.P.}}$ Thus, if

the head be 1 foot, the speed of the 1 H.P. runner or its specific speed, N_s, will be

$$N_s=\frac{\text{R.P.M.}}{h^{1/2}}\times\sqrt{\frac{\text{H.P.}}{h^{3/2}}};$$

or

$$N_s=\text{R.P.M.}\times\frac{\sqrt{\text{H.P.}}}{h^{5/4}}.$$

If it is desired to obtain the specific speed according to the metric system with English units (Ft. and H.P.) used in the formula, multiply the values obtained from the above formula by 4.45. In transferring we have 1 foot equal to $\frac{1}{3.28}$ meter and 1 English H.P. equal to 0.986 metric H.P. Thus

$$N_s=\text{R.P.M.}\times\frac{\sqrt{\text{H.P.}}\times(3.28)^{5/4}}{h^{5/4}\times\sqrt{0.986}}=4.45\times\text{R.P.M.}\times\frac{\sqrt{\text{H.P.}}}{h^{5/4}}.$$

The value $h^{5/4}$ may readily be figured out as follows:

$$h^{5/4}=h\times h^{1/4}=h\sqrt{\sqrt{h}}.$$

The diagram in Fig. 115 supplies a convenient graphic method of deducing the specific speed of a runner from any given set of conditions without the use of the formula.

In figuring the specific speed of a turbine with more than one runner or nozzle, the H.P. used should, of course, be the output from each runner or nozzle. Furthermore, as the above formula applies to single-runner turbines, it follows that in the case of a turbine of the same capacity having n runners of the same specific speed, it is seen that the R.P.M. would be $\sqrt{n}$ times the R.P.M. of the single-runner turbine. It is also readily seen that for a given value of R.P.M., and h, the H.P. output is proportional to the square of the specific speed, and also that for a given head and H.P. the R.P.M. of a turbine is proportional to the specific speed.

By comparison of the specific speeds, it is possible to judge the characteristics of water-wheel runners without considering their actual speed, power, or head. Other things being equal, a high specific speed means a high actual speed, and a low specific speed, a low actual speed in revolutions per minute. With low-head developments, the highest speed compatible with good engineering practice, must be selected in order to keep down the weight, and consequently the cost, of the generators. With very high heads it is mostly a question of keeping the

speed reasonably low so as to avoid the use of costly high-speed generators. The limit of high speed for low-head developments is fixed by the progress of the art of designing high-speed runners, and the limit of

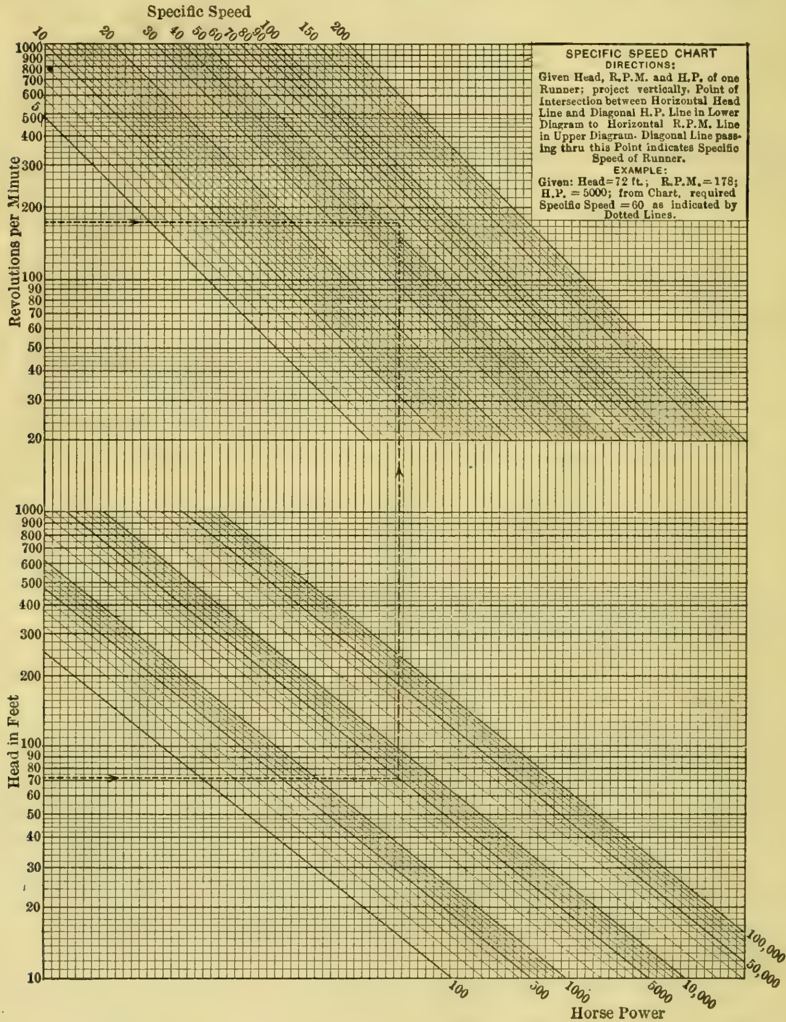


FIG. 115.—Specific Speed Chart.
(By Courtesy of Wellman-Seaver-Morgan Company.)

low speeds under high heads is fixed by the risks involved in designing runners for operation with very low coefficient of specific speed. High speed under low heads also means large discharge capacity per unit diameter, resulting in a large power capacity; while low speeds under

high heads mean a small discharge capacity per unit diameter, resulting in a small width of runner.

Reaction turbines have been built for specific speeds as low as 7; but this represents an exceptional case, and under usual conditions specific speeds of less than 20 are not recommended. Starting at this speed, the efficiency will increase as the specific speed approaches more normal values, the efficiency reaching the highest values between specific speeds of 25 and 75. This applies to turbines of the usual mixed-flow type, sometimes known as "Francis turbines."

Francis turbines may be used for specific speeds in excess of 75; but as the speed is increased the vane formation becomes more complicated, the risk of corrosion increases, and the efficiency drops at a continually increasing rate. Francis turbines are not recommended for specific speeds in excess of 100.

With the new propeller-type turbines, particularly those of the diagonal type, high efficiencies can be obtained and satisfactory conditions of operation secured for greatly increased values of specific speeds, the normal range of values of specific speed for diagonal propeller-type turbines being approximately 100 to 150. Propeller-type turbines can, however, be obtained for both higher and lower values than those included in this range.

In order to indicate the range of specific speeds particularly suited to various values of head, for guidance in the selection of turbine types for plants operating under different heads, Table XXXVIII is given.

TABLE XXXVIII

Based on Usual Accepted Practice, Showing the Range of Heads Suitable for Various Specific Speeds

Range of Specific Speeds, Foot-pounds.	Range of Heads, Feet.
From 20 to 25	Up to 900
20 " 30	" " 450
20 " 40	" " 250
20 " 60	" " 125

In using this table, it should be realized that no hard-and-fast limits can be placed on the specific speeds which may be used under any given head, or on the range in heads for which a given specific speed may be applied. The values tabulated represent the field which has so far been covered in successful practice. The limits of applicability cannot be adequately expressed as a relation merely between

head and specific speed. The feasibility of installing a turbine of a given specific speed is not dependent upon the head on the plant alone, but is, to an even greater extent, dependent upon the draft head on the turbine, as explained in the following section on *draft tubes;* therefore, in order to determine the value of specific speed which is permissible in any given plant, it is necessary to know the height at which the turbine must be placed above low tailwater, and to determine the corresponding degree of vacuum in the draft tube below the runner. If the absolute pressure at this point becomes unduly low, there is serious risk of dangerous corrosion and frequently of unsteady operation and vibration.

For specific speeds in excess of 60, it is difficult to give any definite rule, since the permissible values of specific speed become increasingly dependent upon the elevation above tailwater.

Conditions being otherwise suitable, *propeller-type* turbines can be used for approximately the following values.

For specific speeds up to 100—heads up to 75 feet.

For specific speeds up to 150—heads up to 50 feet.

For impulse turbines of the Pelton type, specific speeds down to very low values may be obtained with good results. The highest efficiencies may perhaps be obtained with specific speeds varying from 1 to 4, and will then be increasingly reduced as the speed is increased up to about $6\frac{1}{2}$ or 7, which might be taken as the extreme limit, the figures applying to single-nozzle wheels. The maximum obtainable efficiencies with an impulse wheel may be taken as between 85 and 89 per cent, these being figures to the center line of the nozzle. More than two nozzles should not be used on a horizontal-shaft wheel, although as many as six nozzles may be used with a vertical shaft wheel.

Not only the number of nozzles, but also the number of runners, and even the number of units, is often increased in order to keep the specific speed low enough to permit the use of impulse turbines. However, recent progress in the design of high-head reaction turbines has been so marked that in a great many instances a reaction unit is installed under conditions which a few years ago would have required an impulse wheel design.

The range of head for which a complete study of all local conditions is required, before a choice between the impulse and the reaction type can be made, has been greatly increased. The highest-head hydraulic prime movers of any kind are four 3000 H.P. impulse turbines of the Pelton type, operating under an effective head of 5320 feet, near Tully, Switzerland; and few modern impulse turbine installations of any considerable size have heads under 400 feet. The exceptional cases occur

where some special conditions exist that are unfavorable to reaction turbines, as when the water carries an excessive amount of silt or contains corrosive chemicals. These substances would cause rapid wear and decreased efficiency in a reaction turbine runner, while the buckets and nozzles of an impulse wheel would be only slightly affected.

The present range of reaction turbines extends from very low heads up to 850 feet. It is claimed, however, by turbine manufacturers, that there is no apparent reason why reaction turbines should not be constructed for head up to, say, 1100 feet, provided other conditions are favorable.

Consider a water-power project with the head somewhere between 400 and 1100 feet, and the horse-power such that some specific speed suitable to reaction turbines will give a generator speed within the limits set by the electrical manufacturers. In general, the following relations will hold:

1. The reaction equipment will be lighter and occupy materially less floor space than the corresponding impulse equipment. The principal reasons for this are the large diameter and weight of impulse wheels for these conditions, also the probable necessity of using two impulse runners, and even two or more units, in order to obtain the same capacity as a single reaction unit.

2. The reaction unit will operate at a higher R.P.M. than the impulse equipment. This will permit the use of a lighter and less expensive generator.

3. Because of the lighter weight of individual pieces of machinery, lighter crane equipment will be permissible with the reaction than with the impulse plant.

4. Lighter turbines and generators decrease cost of foundations; lighter crane equipment decreases cost of superstructure; decreased floor space decreases over-all cost of building.

5. The reaction equipment will have a higher efficiency than the impulse, at loads from three-quarters to full, and possibly over a wider range.

No mention has been made of comparative first cost of the two types, as this cannot be predicted in advance. For the conditions outlined, however, the reaction turbine will be found the least expensive in the majority of instances.

In the past, the following have been important factors in limiting the application of reaction turbines to moderately high heads.

1. Leakage through the clearance space between the runner and the interior of the casing. This leakage increases very rapidly as the head increases, with consequent loss of efficiency.

2. Lower efficiency at fractional loads of reaction, as compared with impulse turbines.

3. Desirability of having several impulse units in a plant, rather than one or two reaction units of the same total capacity. This is more convenient in handling fractional loads, and permits shutdowns of individual units without shutting down the entire plant.

4. Greater ease of making most kinds of repairs and renewals in the impulse type.

Progress in design, as well as change in operating conditions, has reduced the importance of, if not entirely eliminated, the above factors.

Leakage can be eliminated by use of rubber-lined clearance rings. These rings are affixed to the stationary clearance ring inside the casing cover, and bear directly upon the rotating ring attached to the runner, no clearance whatsoever being needed. The friction of wet rubber on wet metal is so small that no lubrication is required. In addition, the erosion of rings because of silt-laden water is reduced, and the danger of unlubricated rubbing of metal rings upon each other is eliminated.

As modern reaction runners give relatively high fractional-load efficiencies, conditions are favorable to impulse wheels for a much smaller part of the load curve than formerly. Perhaps a more important factor, however, is the change in operating conditions that has come to pass. The one-plant company with no interconnections is becoming uncommon; and in its place we have the company operating several plants, and interconnected with several other companies of similar size. Diurnal or seasonal variations in the load curve are met by varying the number of plants in service, not the load on individual units. In addition, an entire plant may be shut down without affecting service, or even overloading the rest of the system. Under such conditions, fractional load efficiencies become relatively unimportant, and, furthermore, a one- or two-unit plant is not objectionable.

Modern reaction turbines are provided with various features facilitating inspection, repairs and renewals. In particular, the single overhung construction for horizontal units permits access to the interior of the turbine without disturbing generator, shaft, or bearings. Similarly, methods have been perfected for the vertical type, permitting removal of a section of the draft tube and giving access to the turbine from below.

A new type of impulse turbine, now in process of commercial development, carries the range of specific speed up to a value of about 50, and may be useful in bridging the gap now existing between the low-speed Francis reaction turbine and the high-speed impulse turbine.

The following elementary examples may be of interest to show the use of the specific speed characteristics.

Assume, for example, an installation having a head of 1900 feet and where the generators would require turbines of 10,000 H.P. capacity running at 375 R.P.M. What type of wheel should be installed?

$$N_s = 375 \times \frac{\sqrt{10,000}}{1900^{5/4}} = 3,$$

and, consequently, an impulse turbine should be selected.

On the other hand, with a 10,000-H.P. wheel to operate at 57.7 R.P.M. under a 32-foot head, we get

$$N_s = 57.7 \times \frac{\sqrt{10,000}}{32^{5/4}} = 76,$$

and a reaction turbine must be used.

In selecting a type of wheel, the number of runners or nozzles, their capacity and speed must be chosen with a view of obtaining not only the highest efficiency, but also the most economical combination of the prime mover and generator. For example, a wheel is to be operated under a head of 400 feet and develop 1500 H.P. How many nozzles should it have, and at what speed may it operate? Assume that a specific speed of 4 will give a good efficiency for the wheel; then the actual speed of the unit will be

$$\text{R.P.M.} = \frac{4 \times 400^{5/4}}{\sqrt{1500}} = 185.$$

This speed, however, may be entirely too low for the generator; and, by providing two nozzles, each supplying 750 H.P. the speed would be increased to

$$\text{R.P.M.} = 185 \times \sqrt{2} = 260.$$

and with four nozzles

$$\text{R.P.M.} = 185 \times \sqrt{4} = 370.$$

Let us see also what the result would be if we tried to apply a reaction turbine running at 720 R.P.M. The specific speed would then be

$$N_s = 720 \times \frac{\sqrt{1500}}{400^{5/4}} = 16,$$

and, consequently, this type would undoubtedly be the most advantageous to use for our case.

The efficiencies, especially at partial load, are related to the specific speed, the curves of high specific speed runners being more pointed than with the low specific speed type, thus allowing a narrower margin for operation under the best conditions. This is clearly shown in the curves in Fig. 116.

The maximum full-load capacity of a tŭrbine is that point beyond which the output decreases with an increase in gate opening. The margin between the point of maximum efficiency and of maximum capacity depends upon the specific speed of the runner, and is smaller the higher the specific speed. This is also illustrated in Fig. 116, which shows that as the specific speed is increased the point at which maximum efficiency occurs approaches nearer to the power delivered at full gate opening. The specific speed may thus be increased to such an

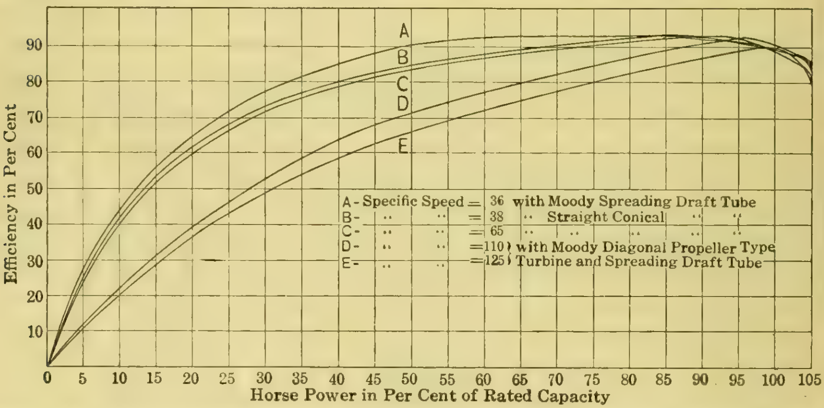


FIG. 116.—Performance Curves of Different Turbines of Different Specific Speed.

extent that the point of maximum efficiency and maximum output coincide. With low heads and high specific speeds it is, therefore, desirable to operate wheels near their point of maximum output; and to obtain the best results, the generator should be designed with consideration to this point.

Referring again to the curves in Fig. 116, it will be noted that the full-load capacity occurs at about 5 per cent above normal or rated full load in all cases. This is in accordance with the general practice, the margin being allowed for governing. It is also noted that the efficiency is falling off very rapidly at 5 per cent overload, and that, should the gate be opened still further, the output would be reduced rather than increased.

For wheels of low or moderate specific speed, as represented by curve A, the efficiency remains very high over a very large range in

power, while for wheels of high specific speed, curves D and E, the efficiency falls off rapidly as the power is reduced below the normal full load. For this reason it is desirable to run low-head wheels under practically full-load conditions. With high-head wheels this is not so important, as the efficiency is still high at partial loads.

The curves plotted in Fig. 116 represent operating conditions under constant head. This, however, is not always realized, especially in low-head plants where floods and dry seasons sometimes cause quite a variation in the head; this has, as previously mentioned, quite a bearing on the selection of the water wheel, and should, therefore, be given careful consideration.

If the speed of the unit could be allowed to vary at all times as the square root of the ratio of the heads, the shape of the performance curve for any head other than normal would be the same as that secured at normal head, but the output would vary as the $\frac{3}{2}$ power of the ratio of the heads. In the case of wheels driving alternating-current generators, a speed variation is not permissible, and the speed must be kept constant irrespective of any variation in head which may occur; this will still further lower the output, owing to the reduced efficiency when operating at the best head and speed.

Curve A, in Fig. 116, represents actual results, from test in place, on the 37,500 H.P. turbines of the Niagara Falls Power Company's Station No. 3, at Niagara Falls. These results are said to represent the highest average efficiency through the full operating range of loads ever developed in a hydraulic turbine.

In Fig. 117 is plotted a set of curves illustrating the effect of a varying head. A 10,000-H.P. turbine is assumed to operate normally under a 32-foot head, the speed to be constant for a range of heads from 26 to 38 feet. As the head goes up to 38 feet, the shape of the curve approaches more closely curve B in Fig. 108, while, when the head falls to 26 feet, the speed being constant, it approaches more closely to curve C. In other words, when operating under a 38-foot head, the speed is lower than the best speed for the runner under that head, while, when operating under the 26-foot head, the speed of the wheel is higher than the best speed. Under 38-foot head the point of maximum efficiency is, furthermore, considerably below the normal full load at that head, while, under 26-foot head, the power at which maximum efficiency occurs is the actual full load, illustrating the points discussed above in reference to the relation of the power at which maximum efficiency occurs and the normal full-load power for various specific speeds.

Let us assume that a selection of a wheel is to be made for an instal-

lation, and that performance curves are desired, showing the expected efficiency for various loads and speeds. Curves A, B, and C, in Fig. 116 may each represent a possible curve, dependent upon the revolutions selected for the turbine in question, the revolutions being directly proportional to the specific speeds, and they will illustrate the manner in which the efficiencies at partial gate openings will fall off in any one case, depending upon the actual revolutions per minute selected for the design of the wheel. They will also give an idea as to the margin between the normal full load and the power at which the points of maximum efficiency will occur. In the selection of a speed for any installation, therefore, aside from the cost of the generators, the question

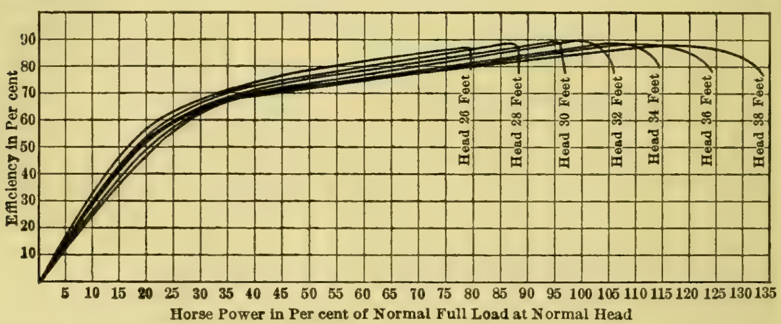


FIG. 117.—10,000 H.P. Francis Turbine-curves Showing Efficiency and Power for Constant Speed and a Normal Head of 32 Feet for Various Heads as Shown.

of the wheel efficiencies at partial gate openings has a considerable bearing. Where a unit is likely to operate under a very wide range in power, it would be advisable to select a wheel represented by curve A, giving a high efficiency for a considerable range in power.

Characteristic Curves. For studying the action of a turbine under different conditions of operation, the characteristic curves, as shown in Figs. 118. 119, and 120, are extensively used, and from these curves it can at a glance be seen at what speed the turbine should be run for the best efficiency at any gate opening.

To show how the curves are constructed, a typical example is given, based on actual tests given in Table XXXIX. The values of the abscissae in the curves represent ϕ, the coefficient of peripheral velocity, although sometimes values of N_1, are used for this purpose. These two quantities are, however, directly proportional, so that the change merely affects the abscissa scale of the curves.

From the report, the values of head, revolutions per minute, horsepower, and efficiency are taken from the corresponding columns for

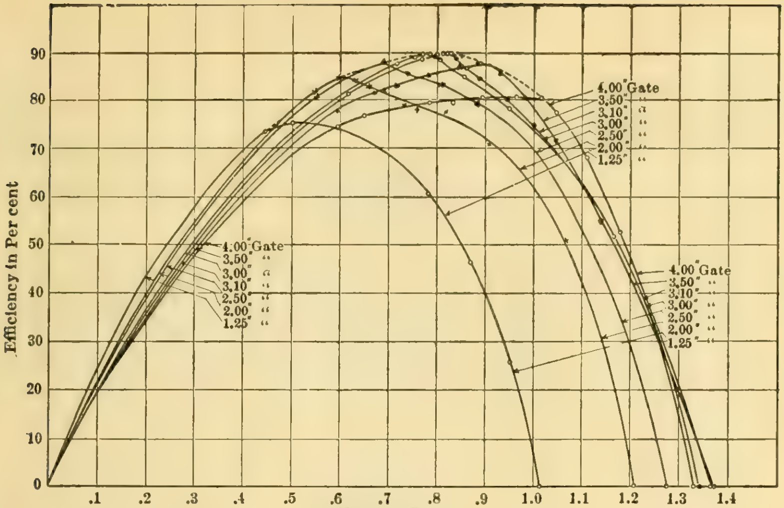


FIG. 118. ϕ-Efficiency Curves of an I.P. Morris Runner

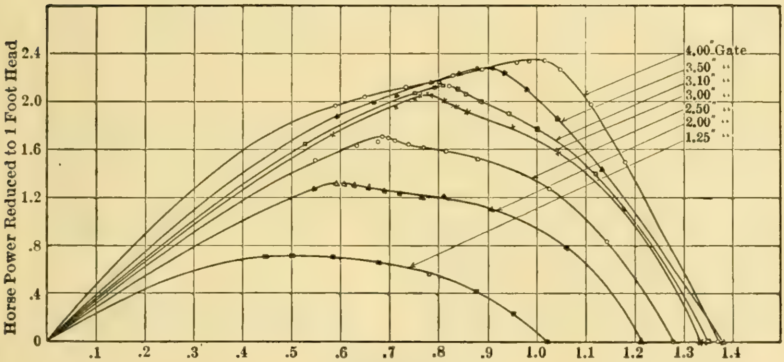


FIG. 119. ϕ-H.P.$_1$ Curves of an I.P. Morris Runner

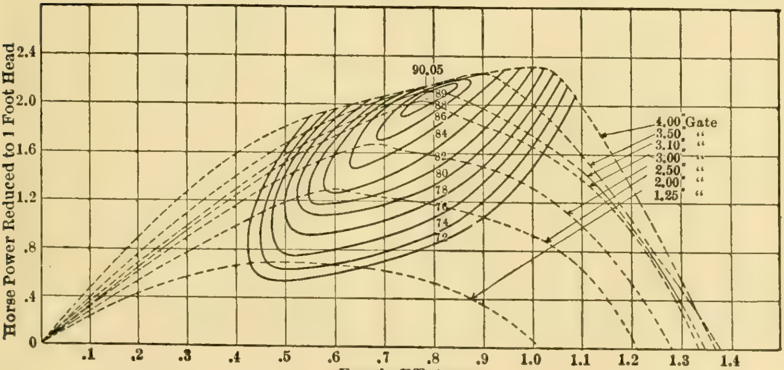


FIG. 120. Equal=Efficiency Contour Curves of an I.P. Morris Runner

the various runs at each gate. From these are computed the corresponding values of ϕ, which is equal to

$$\phi = \frac{\pi D \times \text{R.P.M.}}{60 \times \sqrt{2gh}},$$

in which D is the nominal diameter of the runner in feet—in the case taken, 25 inches or 2.0833 feet—and h is the head in feet. The corresponding values of HP_1, or the horse-power reduced to 1 foot head, are also computed by dividing the given horse-power by the three-halves power of the head, thus

$$HP_1 = \frac{\text{H.P.}}{h^{3/2}}.$$

The result represents the power which the given runner would develop if operated at the corresponding speed, that is, at the same value of ϕ under a head of 1 foot instead of the head used in the test. The ϕ-efficiency and ϕ-HP_1 curves are now plotted for each gate opening, Figs. 118 and 119.

In order to construct the curves of equal efficiency, Fig. 120, the ϕ-HP_1 diagram is selected, and points having the same efficiency on the curves for different gate openings are joined in a curve. In order to keep the diagrams clear, the ϕ-HP_1 curves have been repeated in dotted lines on a separate diagram.

To illustrate the construction of one of the equal efficiency contours, for instance, take the line for 86 per cent efficiency. Referring to the ϕ-efficiency diagram, a horizontal line representing the efficiency selected will intersect the curve for 2.5 gate at $\phi = 0.64$, and will again intersect the same gate at $\phi = 0.725$. Passing to the ϕ-HP_1 diagram, points are located on the 2.5 gate curve at the two values of ϕ just found. These are two points on the desired curve. Similar points of intersection of the 86 per cent efficiency line with the ϕ-efficiency curves for other gates are similarly located, and the resulting points joined up.

The diagram obtained may be viewed as a contour map of a mound or hill, the heights of which, in a direction perpendicular to the paper, may be imagined to represent efficiency. If the hill is imagined to be cut by a plane perpendicular to the paper and intersecting the paper in an ordinate at any given value of ϕ, the resulting intersection will be a performance curve such as one of those plotted in Fig. 117.

In Fig. 117, of course, the horse-power has been stepped up to represent a large runner operating under a given head. The performance curves can be conveniently plotted from the ϕ-efficiency and ϕ-HP_1

TABLE XXXIX

TESTING FLUME OF THE HOLYOKE WATER POWER CO., HOLYOKE, MASS.

Report of tests of a 25-inch Right-hand I.P. Morris Company turbine wheel.

Number of the Experiment.	Opening of the Speed Gate in Inches.	Proportional Part of the Full Discharge of the Wheel in Per Cent.	Head Acting on the Wheel in Feet.	Duration of the Experiment in Minutes.	Revolutions of the Wheel per Minute.	Quantity of Water Discharged by the Wheel. Cu.ft. per Sec.	Power Developed by the Wheel. H.P.	Efficiency of the Wheel in Per Cent.
55	4.00	0.917	17.74	3	182.33	97.79	146.49	74.62
54	4.00	0.924	17.72	3	200.33	98.49	151.27	76.60
53	4.00	0.939	17.71	4	226.75	99.99	157.52	78.61
56	4.00	0.948	17.70	4	241.25	100.92	160.30	79.31
52	4.00	0.961	17.66	4	256.25	102.21	162.53	79.58
51	4.00	0.984	17.52	3	275.00	104.20	166.12	80.42
49	4.00	0.999	17.53	4	295.00	105.85	169.29	80.63
50	4.00	1.005	17.51	4	302.00	106.44	169.66	80.45
48	4.00	1.015	17.48	3	312.67	107.40	169.99	80.02
47	4.00	1.018	17.51	4	321.75	107.76	165.20	77.38
46	4.00	1.006	17.54	4	340.75	106.68	144.09	68.05
45	4.00	0.985	17.60	4	362.50	104.56	109.49	52.58
43	3.50	0.837	17.84	4	183.75	89.52	140.97	78.01
42	3.50	0.850	17.83	3	206.33	90.87	149.56	81.58
44	3.50	0.860	17.76	4	221.50	91.76	153.87	83.44
41	3.50	0.862	17.78	4	221.75	91.99	154.04	83.23
38	3.50	0.877	17.79	4	241.50	93.57	160.47	85.20
37	3.50	0.894	17.72	4	261.50	95.27	165.86	86.83
40	3.50	0.905	17.67	5	272.80	96.29	168.09	87.31
39	3.50	0.911	17.67	4	279.75	96.87	168.99	87.25
36	3.50	0.909	17.69	4	287.75	96.76	165.14	85.26
35	3.50	0.906	17.69	4	302.25	96.41	155.19	80.42
34	3.50	0.897	17.71	4	323.00	95.50	136.58	71.37
33	3.50	0.879	17.75	4	351.50	93.68	106.16	56.42
82	3.10	0.784	17.88	5	191.20	83.80	138.60	81.65
75	3.10	0.814	17.75	4	236.75	86.75	154.45	88.65
76	3.10	0.821	17.75	5	244.80	87.53	156.75	89.26
77	3.10	0.821	17.75	5	246.80	87.53	157.28	89.57
74	3.10	0.824	17.73	4	249.75	87.86	158.41	89.82
81	3.10	0.824	17.73	4	250.00	87.97	158.57	89.59
78	3.10	0.827	17.73	4	251.00	88.08	158.44	89.67
79	3.10	0.828	17.72	5	252.40	88.19	158.56	89.67
80	3.10	0.827	17.75	4	254.25	88.19	158.96	89.74

TABLE XXXIX—*Continued*

TESTING FLUME OF THE HOLYOKE WATER POWER CO., HOLYOKE, MASS.

Report of tests of a 25-inch Right-hand I.P. Morris Company turbine wheel.

Number of the Experiment.	Opening of the Speed Gate in Inches.	Proportional Part of the Full Discharge of the Wheel in Per Cent.	Head Acting on the Wheel in Feet.	Duration of the Experiment in Minutes.	Revolutions of the Wheel per Minute.	Quantity of Water Discharged by the Wheel. Cu.ft. per Sec.	Power Developed by the Wheel. H.P.	Efficiency of the Wheel in Per Cent.
73	3.10	0.824	17.74	4	256.75	87.86	156.30	88.62
72	3.10	0.823	17.75	4	265.75	87.75	152.50	86.53
71	3.10	0.823	17.76	3	274.00	87.75	148.96	84.47
70	3.10	0.820	17.77	4	187.53	87.53	140.87	80.04
69	3.10	0.820	17.77	4	309.50	87.53	130.87	74.36
68	3.10	0.817	17.80	4	346.25	87.20	104.58	59.54
25	3.00	0.750	17.98	4	181.00	80.31	130.11	79.00
20	3.00	0.776	17.87	4	221.25	83.02	147.01	87.58
23	3.00	0.785	17.83	4	233.25	83.90	150.76	89.07
22	3.00	0.790	17.83	3	239.00	84.44	153.03	89.83
19	3.00	0.791	17.85	4	242.00	84.55	153.48	89.88
21	3.00	0.792	17.83	4	242.50	84.66	153.81	90.05
24	3.00	0.792	17.81	4	243.00	84.55	152.66	89.59
18	3.00	0.790	17.85	4	249.50	84.44	150.71	88.37
17	3.00	0.788	17.86	4	257.25	84.23	147.63	86.73
16	3.00	0.784	17.86	10	265.10	83.90	144.12	85.00
15	3.00	0.786	17.84	3	293.67	84.01	133.05	78.45
14	3.00	0.787	17.84	4	323.25	84.12	117.16	68.99
13	3.00	0.780	17.87	3	361.00	83.46	87.23	51.69
9	2.50	0.647	18.12	4	169.75	69.69	114.85	80.37
8	2.50	0.662	18.07	4	197.00	71.24	124.95	85.78
7	2.50	0.668	18.06	3	210.67	71.86	127.26	86.56
12	2.50	0.669	18.03	5	213.20	71.86	128.79	87.85
10	2.50	0.670	18.04	6	217.50	72.06	128.76	87.53
6	2.50	0.666	18.07	5	221.80	71.65	127.28	86.88
5	2.50	0.664	18.07	4	230.00	71.44	126.04	86.80
4	2.50	0.662	18.07	4	240.00	71.24	123.23	84.60
3	2.50	0.665	18.05	4	251.75	71.55	121.66	83.25
2	2.50	0.665	18.07	4	274.50	71.55	116.07	79.34
1	2.50	0.665	18.05	3	320.00	71.55	96.65	66.14
11	2.50	0.657	18.10	4	356.50	70.72	64.60	44.60
66	2.00	0.538	18.26	4	171.50	58.16	98.42	81.90
67	2.00	0.542	18.24	4	186.25	58.55	102.38	84.72

TABLE XXXIX—*Continued*

TESTING FLUME OF THE HOLYOKE WATER POWER CO., HOLYOKE, MASS.

Report of tests of a 25 Right-hand I. P. Morris Company turbine wheel.

Number of the Experiment.	Opening of the Speed Gate in Inches.	Proportional Part of the Full Discharge of the Wheel in Per Cent.	Heat Acting on the Wheel in Feet.	Duration of the Experiment in Minutes.	Revolution of the Wheel per Minute.	Quantity of Water Discharged by the Wheel. Cu.ft. per Sec.	Power Developed by the Wheel. H.P.	Efficiency of the Wheel in Per Cent.
65	2.00	0.542	18.25	4	188.75	58.64	102.62	84.74
64	2.00	0.537	18.28	4	196.75	58.16	101.02	83.98
63	2.00	0.535	18.29	5	205.40	57.87	99.26	82.88
62	2.00	0.535	18.29	4	216.50	57.87	98.09	81.90
61	2.00	0.534	18.40	4	226.00	57.78	95.56	79.87
60	2.00	0.532	18.31	5	238.40	57.59	93.61	78.45
59	2.00	0.535	18.31	4	255.75	57.97	92.69	77.18
58	2.00	0.538	18.32	4	284.75	58.26	86.00	71.21
57	2.00	0.533	18.33	5	334.40	57.78	60.60	50.57
32	1.25	0.332	18.53	3	142.00	36.18	55.76	73.50
31	1.25	0.332	18.65	3	158.33	36.26	57.39	74.99
30	1.25	0.326	18.66	3	185.00	35.69	55.88	74.15
29	1.25	0.323	18.65	3	215.00	35.29	51.95	69.76
28	1.25	0.318	18.65	3	247.33	34.80	44.82	61.03
27	1.25	0.315	18.65	3	276.33	34.39	33.38	46.00
26	1.25	0.310	18.65	3	302.33	33.83	18.26	25.58
89	4.00	0.915	17.65	4	423.00	97.33		
88	3.50	0.842	17.80	4	426.50	89.86		
87	3.10	0.751	17.95	3	418.67	80.52		
86	3.00	0.720	18.02	4	415.75	77.31		
85	2.50	0.604	18.21	4	401.25	65.23		
84	2.00	0.482	18.39	4	381.50	32.28		
83	1.25	0.305	18.70	4	323.50	33.35		

curves by finding the corresponding values of HP_1 and efficiency for certain required values of ϕ which are determined by the head and speed in a given installation.

Speed Regulation.[1] The most generally used method for governing the speed of reaction turbines is by means of wicket gates or guide vanes which change the amount of water supplied by simply altering the water passages (see Fig. 121). The vanes rotate about pivots and are fastened to a shifting ring by link motion, the ring being operated by pressure cylinders, actuated by the governor. If the velocity of the water

[1] See also sections on "Governors" and "Waterhammer."

is checked too suddenly, dangerous pressures may be set up in the pipe lines and the speed regulation may be affected. In order to avoid this, relief valves are often provided, either of the pressure or the synchronous by-pass type. The former is analogous to the safety valve on a boiler and does not open until a certain pressure has been obtained. The latter, however, is operated by the governor at the same time as the turbine gates, but in opposite direction, thus affording a by-pass, so that there is no reduction in the flow. To prevent waste of water, these by-passes may be slowly closed by some auxiliary device. It is obvious, however, that such water-saving relief valves are inoperative

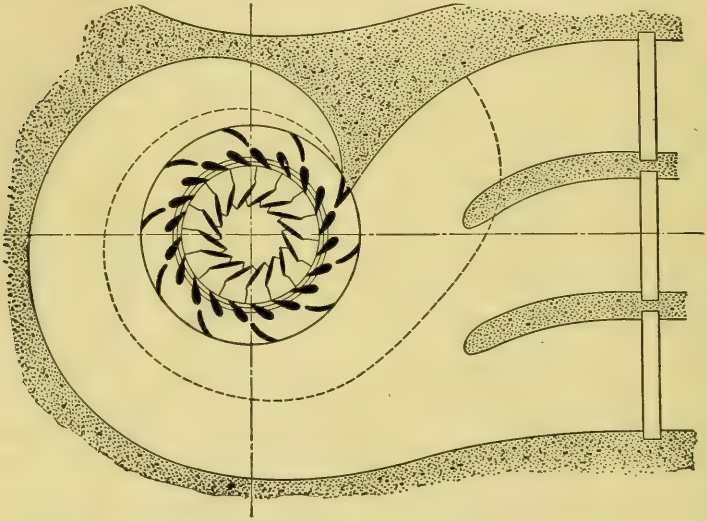


Fig. 121.—Typical Arrangment of Vertical Reaction Turbine, Showing Relation of Wicket Guide Vanes to Casing and Runner.

when the load is thrown on, and, therefore, cannot then assist the speed governor or prevent surges in the pipe lines caused by the same. For preventing these, surge tanks or sufficient flywheel effect of the turbine unit must be relied upon.

For the speed regulation of impulse wheels there are two methods in general use, viz.:

1. Hand-regulated needle nozzle with jet deflector.
2. Auxiliary relief needle nozzle.

The deflecting nozzle has become obsolete for several reasons. The nozzle body was heavy and the effort required to move it called for a large and expensive governor, while, on the other hand, it was difficult to obtain the quick movements essential to accurate regulation.

Either of the above two methods of regulation involves the use of the characteristic needle and nozzle tip, a sectional view of which is shown in Fig. 122. The full lines illustrate the position of the needle when the nozzle is closed, and the dotted lines the needle position with the jet discharging.

The first system consists of a nozzle body in which is inserted a concentric tapered needle, as just described. By means of this needle, which is manually controlled for this type of nozzle, the jet area is adjusted intermittently to correspond to either the stream-flow or the maximum anticipated load likely to be carried within a certain time limit. The automatic speed regulation is obtained by means of a governor, actuating a deflector, which is placed in front of the nozzle tip and regulates the speed by intercepting or deflecting the stream. It is, therefore, obvious that this system of regulation does not permit of any economy in the water consumption, unless the station attendant frequently changes the needle adjustment by following closely the load curve. It is, therefore, mainly intended for plants that are located on streams where water storage is not feasible, or where other power plants are located on the same stream, making it necessary to allow the full flow of the stream to pass the plant, or on those streams where irrigators' or riparian rights have a prime control, thus preventing the storage of water.

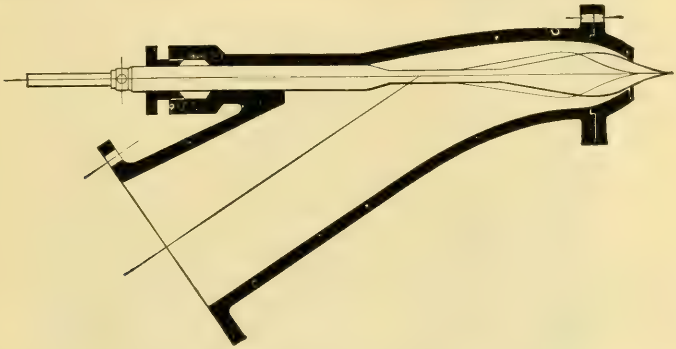


FIG. 122.—Sectional View of Pelton Needle Nozzle.

The needle is usually operated by hand control, being set to utilize to full advantage the available supply of water, where there are forebay reservoirs, economy in the use of water is secured by setting the needle at different times during the day to carry the maximum load on the plant, the needle being set to follow the general load curve of the plant, while the momentary load changes and speed control are taken care of by the governor operating the jet deflector.

In plants where large units are installed, the needle setting may be controlled by means of an electric motor with remote control from the switchboard, so that the power plant operator can, from the switch-

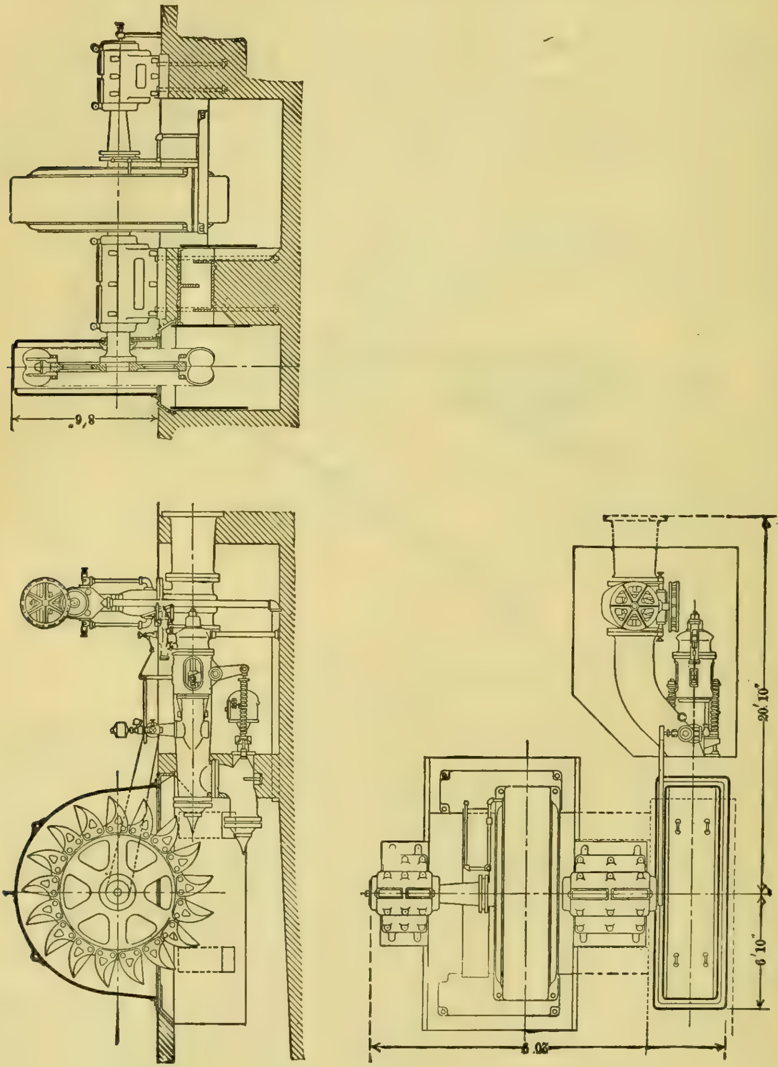


FIG. 123.—14,000 H.P. Pelton Water Wheel Unit with Auxiliary Relief Needle Nozzle.

board, set the position of the needle so as to carry any predetermined load that is desired. The needle setting is changed from time to time as the general condition of the load changes. In such plants, the over-

all consumption of water approximates, in a series of steps, the load curve on the mover.

The ideal type of nozzle, and the one that insures the most sensitive speed regulation and highest economy of water consumption, is, however, the "auxiliary relief needle nozzle," Figs. 123 and 124. This consists of a main needle nozzle and a synchronous by-pass in the form of an auxiliary needle nozzle which discharges into the tailrace. Both nozzles are operated simultaneously, but in opposite directions, by the power mechanism of the speed governor. The auxiliary nozzle opens when the power nozzle closes and vice versa, the volumetric relationship between the two being adjustable, according to the conditions at the

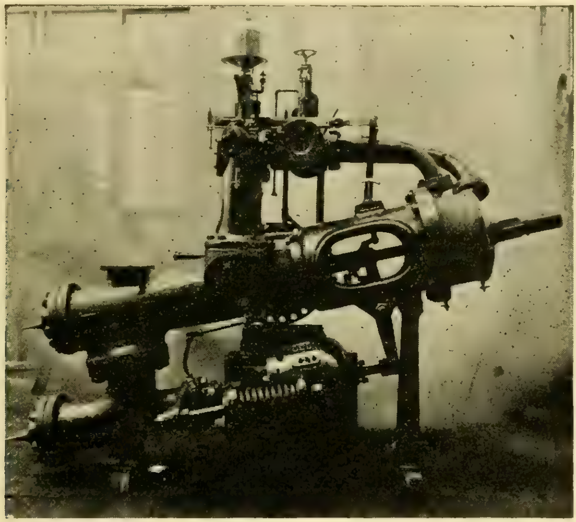


FIG. 124.—Pelton Auxiliary Relief Needle Nozzle.

plant. This, in itself, would prevent any pressure rise in the pipe conduit, but would not afford any economy in water consumption. In order to save water, it is necessary to keep the auxiliary relief nozzle closed during a partial or slow motion of the main needle. In addition, when the relief nozzle has been opened, it should close as rapidly as is consistent with safety to the pipe line.

Run-away Speed. Owing to the action of the governor, the normal speed of the turbine is usually maintained constant under operating conditions. However, if the load changes take place without a corresponding regulation of the admitted quantity of water, the speed will necessarily vary, increasing as the load decreases and vice versa. If

the load should suddenly drop off with the gates wide open and remain so for some reason or other, the speed will rise considerably, sometimes resulting in disaster to the direct-connected generators, and these should, therefore, always be designed safely to withstand such run-away speeds of the water wheels. These depend to a great extent on the hydraulic development and the type of wheel used. For high-head plants, where impulse wheels are used, the run-away speed should preferably be estimated at double normal speed. For low heads, with Francis reaction turbines, when they are working at the most efficient speed, and the head is constant, the run-away speed may be from 50 to 80 per cent above normal speed. Under low-head conditions with a wide variation in the head, and with the wheels designed for an intermediate speed to work under these different conditions, a run-away speed up to twice normal may be realized under the maximum head.

The new propeller-type turbines may develop run-away speeds from 2 to $2\frac{1}{2}$ times the normal speed under a constant head. It is this very possibility of developing high run-away speed which enables turbines of this type to maintain a high power output under conditions of impaired head on a plant, due to flood conditions with rising tailwater.

The above values are only general; and it is most desirable that in all cases a detailed analysis be made, based on test data for the particular type of wheel which is to be used, and considering the extreme range of heads and the other conditions under which the wheel is to operate.

To prevent dangerous run-away speeds several types of run-away speed devices may be used. One of these consists of a fly-ball mechanism, independent of the turbine governor, driven from the shaft of the unit which, in the event of excessive speeds, by means of control valves admits water behind the piston in an auxiliary cylinder on the governor. This causes it to move in such a manner as to overcome the oil pressure in the control element of the governor and shut down the unit. The only completely safe procedure is, however, to construct both turbine and generator so that no excessive stresses will be developed at run-away speed under the highest head which will occur in the plant. This principle is much safer than reliance on automatic devices which, on account of their infrequent use, are in danger of failing to operate when the necessity arises.

Mechanical Design. *Reaction type:* Turbines of this type may be divided into two classes: horizontal and vertical. The horizontal setting is now practically obsolete, however, for large installations in this country; and even in foreign developments there is a marked tendency towards vertical units. For replacing old horizontal wheels or in adding units to old horizontal plants, horizontal turbines are still being

built; but even under these conditions many vertical turbines are installed. Vertical installations are superior not only in the efficiency obtainable and in simplicity of mechanical operation, but also from the point of view of first cost.

Horizontal Turbines: The simplest form of the multi-runner horizontal turbine was the open flume type. This was, however, open to the objection that the gate mechanism was submerged and could not be efficiently lubricated, while the entire machine was inaccessible for inspection and repairs. The most approved type has been the

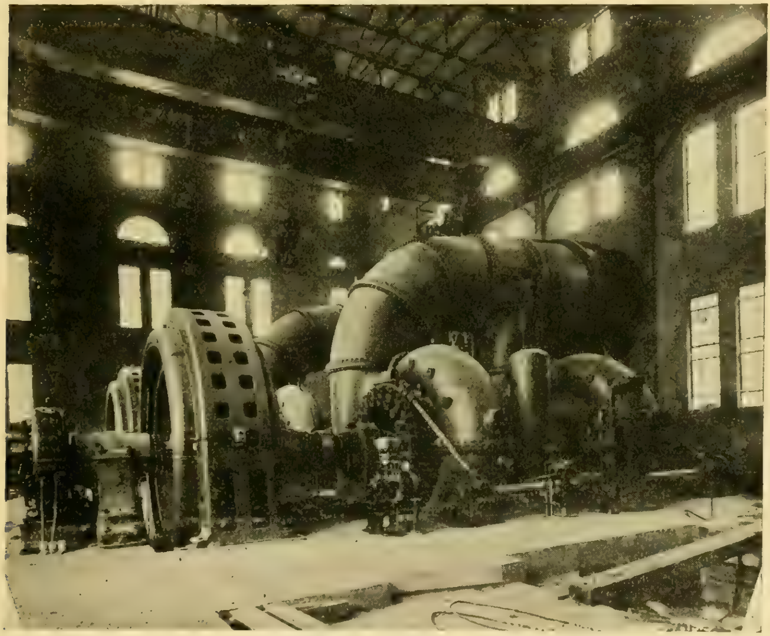


Fig. 125.—Double-Runner 22,500 H.P. Horizontal Turbine with Cast-iron Spiral Cases and One Common Discharge Tube. Long Lake Station of the Washington Power Company. (Built by the I. P. Morris Company.)

volute or spiral casing construction, with single or double discharge, both admitting of an exposed gate mechanism. Figure 125 shows a horizontal double runner turbine with one common discharge tube.

Vertical Turbines. The vertical shaft multiple-runner type of turbine has become practically obsolete, and for all new installations the single-runner vertical type is recommended. As described in greater detail later, the casing is of volute or spiral form, and for low heads is usually molded in the concrete foundations of the power-house (Fig. 126). For higher heads it is made of cast-iron, cast-steel or

riveted-steel plate, as conditions may require. Sometimes the metal casing is imbedded in concrete under the floor which supports the generator. The thrust bearing is usually placed on top of the generator, and supported by a truss construction on the generator frame. The gate mechanism is of the exposed type, no parts being in the water except the gates themselves, and all bearings and pin connections are accessible for lubrication.

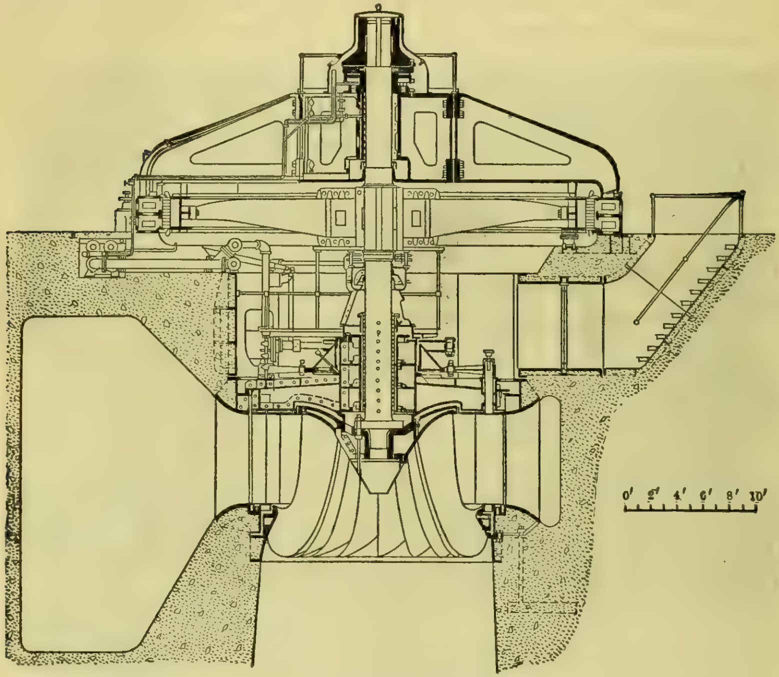


FIG. 126.—Single-runner Vertical Turbine with Volute Casing and Draft Tube Molded in the Concrete Substructure.

Runners. As previously mentioned, turbine runners are classified as of the Francis type and the propeller type. The former may, in turn, be divided into low, medium, and high-head runners, depending on the specific speed for which they are designed, while the propeller type is ordinarily intended for very high speeds. The general form of these several types has been shown in Figs. 111 to 114; Figs. 127 to 129 also show typical runners as actually constructed.

The propeller type runner shown is of the Moody diagonal design, in which the flow is in a diagonal direction towards the axis of the turbine. This type of runner was developed to meet the demand for

higher speed runners. As the name implies, it resembles a propeller in general appearance and has from 3 to 8 vanes, as compared to the 14 to 24 vanes of the Francis type, the exact number depending on the specific speed of the runner, the head under which it operates and the problem of pitting. The openings are therefore twice as great, resulting in less danger from clogging with foreign material, also allowing greater spacings of the intake trash racks. It is much smaller and stronger and, for the same power, weighs only about one-half as much as the Francis type. On account of the higher speed, the cost of the generator

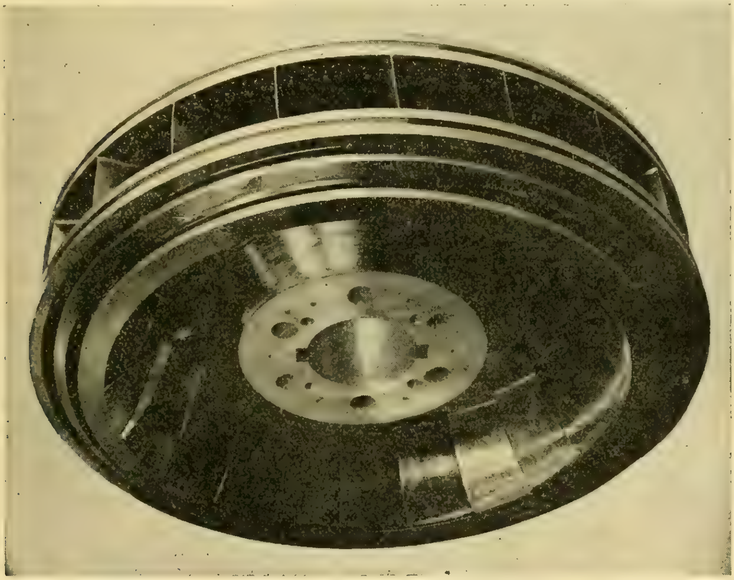


Fig. 127.—Low Specific Speed Runner. 30,000 H.P., 428 R.P.M., 680 Ft. Head. (Manufactured by I. P. Morris Company.)

is also less, and the foundations, superstructure, etc., can also be made smaller and lighter.

It is considered best practice to use runners made in one solid casting, the vanes being cast in one pouring, together with the band and hub. This makes a very strong construction. For the very largest sizes, it may be necessary to make the runners in sections, on account of shipping limitations and so as to assure sound castings. No shrouding band is necessary with the propeller type runner, and separate vanes can be used, bolted to a central hub. These can be readily replaced if broken.

Correct design of the runner vanes and water passages is more important than the material in avoiding corrosion. Cast-iron is generally considered satisfactory for heads of 200 feet or less. On account of its mechanical strength, however, cast steel is extensively used for runners under intermediate heads, where the size or speed of the turbine is such that high stresses are produced in the runner, and where there are other reasons for desiring high mechanical strength, such as the presence of a large amount of trash in the water. For high heads, one of the larger turbine manufacturers prefer a special bronze alloy, as having a greatly increased resistance to corrosion, as compared to either cast-iron or steel. Cast-steel is also extensively used in high-head runners.

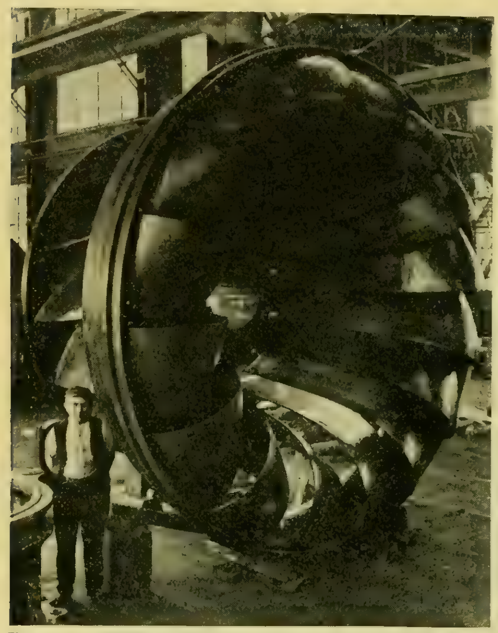


Fig. 128.—High Specific Speed Runner. 30,000 H.P., 100 R.P.M., 100 Ft. Head. (Built by I. P. Morris Company.)

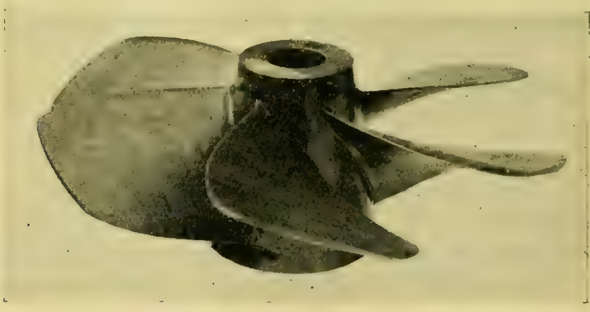


Fig. 129—Very High Specific-speed Propeller Type Runner. (Built by I. P. Morris Co.)

Damage to turbine runners may be caused by both corrosion and erosion, the two being of an entirely different nature. Mr. H. B.

Taylor explains their difference as follows: " Erosion is entirely a mechanical action, while corrosion, or pitting, is the result of chemical action. The abrasive action of foreign substances in the water has the effect of first polishing the vane surfaces, and eventually cutting away the metal until the vanes are worn entirely through. The eroded parts are, therefore, smooth and can be readily distinguished from the pitted marks which result from corrosion.

" It has been demonstrated that corrosion is primarily a question of design and it has been clearly shown in practice that where sharp curves are resorted to, where contraction is not sufficient, or where there are pockets formed in the surface of the vanes, pitting or corrosion inevitably develops. It has also been demonstrated that where air in large quantities is entrained in the water carried to the turbine corrosion seems to take place very rapidly if the design is not correct.

" A corroded vane surface has an appearance resembling a sponge, the surface being extremely irregular and the pitted spots often opening holes entirely through the vane. Chemical analysis of the corroded surfaces has brought out the fact that the metal has been oxidized. In runners made of bronze or an alloy, modifications in the composition have been detected in the corroded portions.

" The theory of corrosion, as now generally accepted, is that the water in passing over any pocket or depressed surface, or in failing to adhere to the surface of the vane, leaves spaces which are filled with eddies possessing high velocities and very low static pressure, in which oxygen is liberated from the water. This oxygen is believed to be in the nascent state and rapidly attacks the surface of the metal, forming an oxide coating, the greater part of which is rapidly washed away by the water. When once the depth of this pocket is increased by corrosion, it is natural that, due to the greater area exposed, the pitting action should continue at an accelerated rate until the vane is entirely eaten through."

Gate Mechanism. Wicket or swivel gates, Fig. 130, are now the only type used with reaction turbines. They are controlled by links and levers to one common shifting ring, which in turn is operated by the regulating cylinders or so-called "servo motors" of the governor system, two of these being generally used for larger turbines. These are attached to the ring at diametrically opposite points, so as to insure a balanced condition. The operating mechanism is entirely exposed and all the bearings may be lubricated and the gate-stem packings arranged to exclude water and grit.

The wicket gates, or movable guide vanes, are mostly made of cast steel. They are subjected to rough usage on account of ice, stones

and rubbish in the water, and cast iron is too brittle for such service. In very large units, the gate stems or fulcrums should be detachable from the gates. The stem may then be withdrawn from the gate and the latter removed without disturbing the crown plate of the turbine. This is a great convenience but, unfortunately, is feasible only in connection with large units; on smaller work the stems must either be cast or forged integral with the gates. The gate stems must, furthermore, be of ample strength to resist the strain in case an obstruction is caught between two gates and the full power of the governor is concentrated upon them. The links which connect the gate-stem levers to the operating ring should be the weakest element of the gate mechanism, and should be designed to break before the stress reaches the elastic limit of the material of any of the other parts.

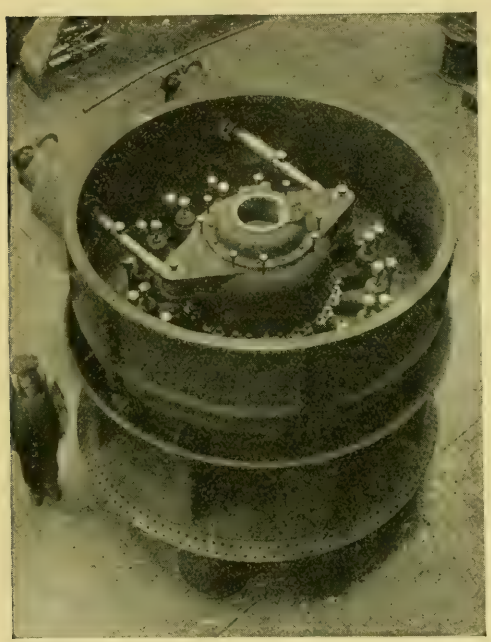


Fig. 130.—Vertical Reaction Turbine, Showing the Gate-operating Mechanism and Speed-ring. (Manufactured by Wellman-Seaver-Morgan Company.)

A new type of operating gear (Fig. 131) has been developed by the I. P. Morris Company, in which the lever attached to the guide vane is offset from its usual radial position and, as the vane closes, turns further away from the radial position. By thus using links in compression, a toggle action is obtained which gives the desirable feature of a greater angular turn of the vane at large loads than at small loads, and also a maximum

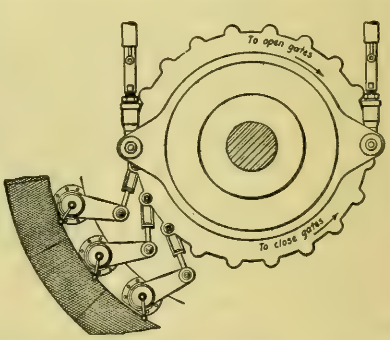


Fig. 131.—Gate-operating Mechanism of the Offset-lever Type.

torque on vane in closed position, resulting in improved speed regulation. A shearing action in the links also gives protection against injury due to a block vane.

For lubricating the internal parts of high-head units, the same company has also developed a large, pneumatically operated grease gun, with piping to the guide vane bearings, etc., which insures sufficient pressure to force grease in against the head, which is difficult and slow with hand-operated cups.

Speed Rings. Speed rings, or stay-vane rings, as they are also called, were introduced in connection with the large single-runner vertical turbine with volute casings molded directly in the concrete. They consist of a series of curved vanes outside of the turbine guide vanes, forming, together with an upper and lower crown (Figs. 121 and 130), a rigid frame to support the weight of the portions of the turbine and of the concrete substructure of the power-house located above the casing, as well as the generator and thrust bearing. The vanes are shaped to suit the free passage of water entering the movable guide vanes. This arrangement is preferable in every way to round stay bolts, the large, projected area and circular form of which causes considerable hydraulic losses. Besides this, there is a mechanical advantage in the use of a rigid cast-iron connection between the upper and lower speed-ring crowns.

A cast-iron cylinder of heavy ribbed design is sometimes inserted between the generator frame and the speed ring of the turbine, to support the former, thereby transmitting the weight of the generator through the cylinder to the speed ring and foundation below. It also connects the wheel and generator rigidly together.

In one of the latest installations, where several large propeller-type turbines are used, the speed rings are not solid, as described above, but the speed vanes are cast separately, and the ends embedded in the concrete and anchored by long foundation bolts. Lugs are cast on the vanes at the top and fitted with adjusting screws for the proper setting of the pit liner with relation to the draft tube ring. It is claimed that, for economic reasons, this new construction may only be applicable to large units.

Casings. The most efficient form of turbine casing in use at present is that of volute or spiral type with which it has become possible to determine definitely the velocity of flow at every point, and to avoid all sudden changes in direction or velocity. The materials most commonly used for medium and high heads are cast iron and cast steel, the choice between them being influenced chiefly by consideration of the stresses imposed. Large casings for high heads are usually made

of cast steel. Cast iron, although more suitable for medium heads, may properly be used for high heads if the casings are small and the material is worked at low stress to provide an ample factor of safety against pressure surges which are of more common occurrence in high-head than in low-head plants.

As compared to plate steel, cast-iron casings have certain advantages, such as the lack of rigidity of the plate steel, its danger of local weaknesses at the riveted joints, possibility of corrosion and leakage

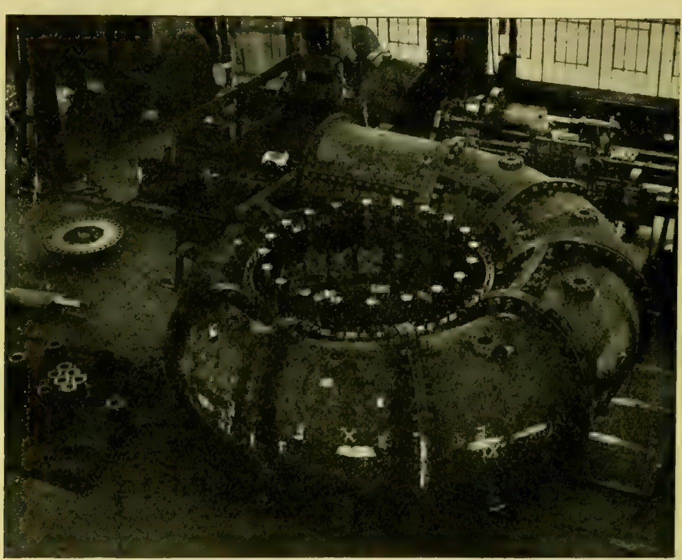


FIG. 132.—Casing for 55,000 H.P. Turbine for Queenston Plant of the Hydro-Electric Power Commission of Ontario; Showing Taylor Method of Sectionalizing.

developing undetected, especially corrosion on the outside surface. Cast casings have, furthermore, the advantage that they may be tested in the shops to a hydrostatic pressure well in excess of that to which they can be subjected after installation. On account of their strength and rigidity, they can also serve as an excellent bed-plate for the entire unit.

Owing to the enormous size of some units and the high head under which they may operate, special construction of the casing is occasionally required, to avoid excessive stresses. It may thus be necessary to divide the casing into a number of radial sections, and the larger of these may in turn have to be further divided into parts (Fig. 132).

For low heads, and especially with large turbines, the casings are

usually molded in the concrete foundations of the power-house (Figs. 133 and 134). If the casings are large enough and the head high enough to produce serious stresses in the concrete, they may be made of metal and imbedded in the concrete. The principal controlling factor in this case is the relative cost of such casings as compared with the cost of adequate reinforcing steel for the concrete, which would be required if the metal lining were omitted.

Where the intake openings are large, it has become general practice to divide the openings by means of vertical piers in a number of channels (Fig. 135). This insures a more uniform distribution of the water

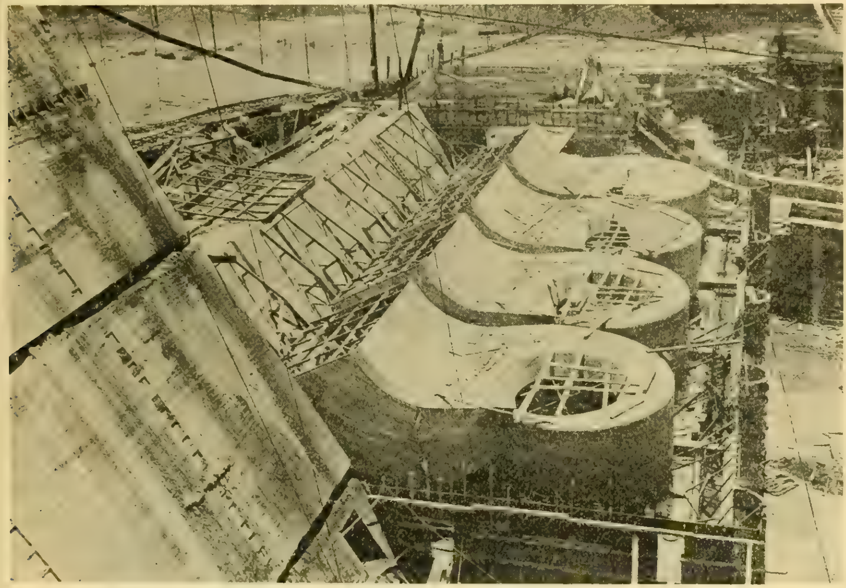


FIG. 133.—Wooden Forms for Concrete Turbine Casings.

around the runner, while, on the other hand, it strengthens the casing by subdividing the span. It also greatly facilitates the application of the gates, which otherwise would be of a size hardly possible to manipulate.

Draft Tubes. A correct draft-tube design is absolutely essential in order to obtain the maximum efficiency of a turbine as a whole. It is an integral part of the design of the turbine and should be furnished by the turbine builder.

The function of the draft tube is, first, to form an air-tight passageway for the water, from the runner to a point below the surface of the tailwater, so as to produce a suction action at the discharge from

the runner at least equal to the difference of elevation between the runner and the level of the surface of the tailwater. It must also transform the energy which is contained in the water discharged from the runner, in the form of velocity head, into energy in the form of pressure head. The fundamental principles underlying the design and construction of a draft tube are, therefore, that the water shall leave

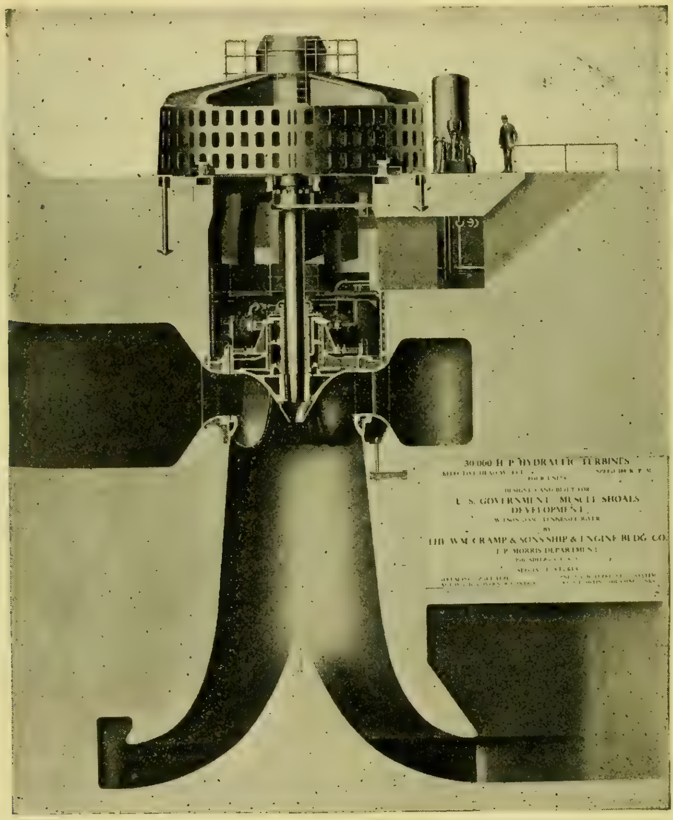


FIG. 134.—30,000 H.P., 100 R.P.M. I. P. Morris Turbine. U. S. Government Muscle Shoals Development. 95 Feet Effective Head.

it with as small velocity as possible. This has in the past been more or less effectively accomplished by the bent draft tube, which design is now, however, being more and more superseded by tubes symmetrical about the turbine axle.

The water leaving the runner is whirling in the direction in which the runner rotates, the center of the vortex being the vertical axis of the draft tube. This vortex tends to remain in the same plane, owing to

its gyroscopic properties, and will not, therefore, follow the center line of the curved type. Serious eddies are likely to be set up by the abrupt turning of the axial component, and the whirl will also set up large eddies. Not only does this reduce the effective discharge area of the tube, but water from the tailrace may actually flow in the reverse direction back into part of the horizontal discharge passage of the tube, thus causing serious eddy losses and high outflow losses.

The ideal tubes are, therefore, the symmetrical ones referred to. Two such designs are now in general use, known respectively as the

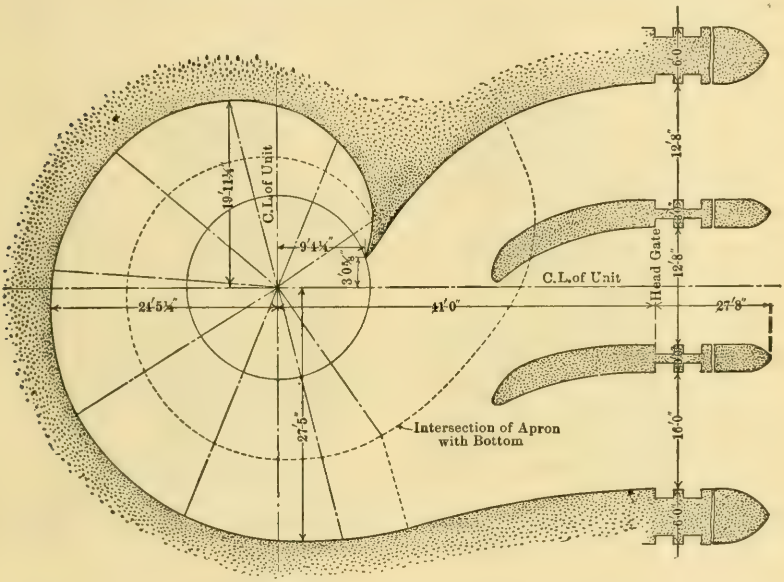


FIG. 135.—Sectional Plan of Cedars Rapids Wheel Chambers.

Moody spreading type and the White hydraucone type. The comparative design is shown in Fig. 136. For the most recent designs of the spreading type, the cone is carried clear up to the runner.

In the Francis turbine, the direction of flow is radial at the intake to the runner, and axial at the discharge. In the propeller type, however, it is the same at the intake and the outlet of the runner, being in a more or less diagonal direction towards the axis of the turbine. As previously stated, the water leaving the runner has also a whirling motion around the turbine axis and if this freely whirling water is permitted to approach the axis closely, low pressures may occur at this point, and may lead to cavitation or formation of voids in the water

stream, with tendencies towards eddy formation, air pockets, and danger of vibration.

The spreading draft tube is designed to gradually decelerate the axial components, smoothly turning them in a radial direction, at the same time continuously decelerating the whirl components by carrying the flow to greater and greater radial distances from the axis, without disturbing the whirling motion until the velocity has been reduced to a low value. By thus turning the flow in an outward direction, away from the axis, the velocity of whirl will diminish in inverse proportion to the increasing radius, and the corresponding velocity head will diminish inversely as the square of the radius, so that it is merely

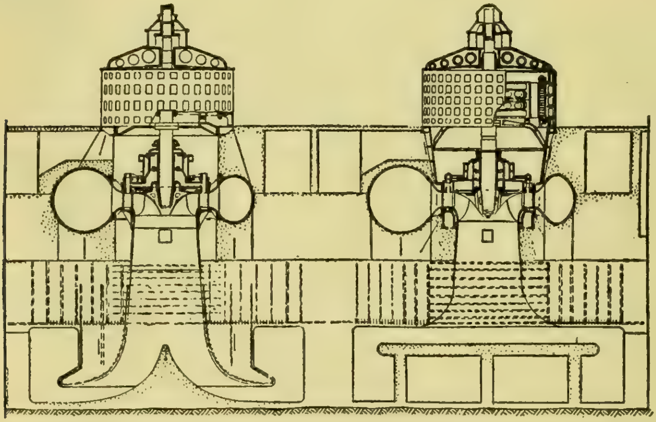


FIG. 136.—Modern Draft Tube Design. Moody Spreading Type (left) and White Hydraucone Type (right).

necessary to lead the water a moderate distance away from the axis to obtain the conversion of a large proportion of the velocity head of whirl into pressure head. After the flow has thus been decelerated in a spreading annular passage along the lines of a free vortex, the water flow is then collected in a spiral or double spiral passage and discharged horizontally into the tailrace.

To provide against the tendency toward the formation of a central cavity within the flowing stream, due to the whirling motion, it is desirable, when structurally feasible, with provide in the draft tube a central core continuous with the runner. Such a design is shown in Fig. 137.

In the hydraucone type, the water is made to impinge against a large flat plate, perpendicular to the axis of the turbine discharge,

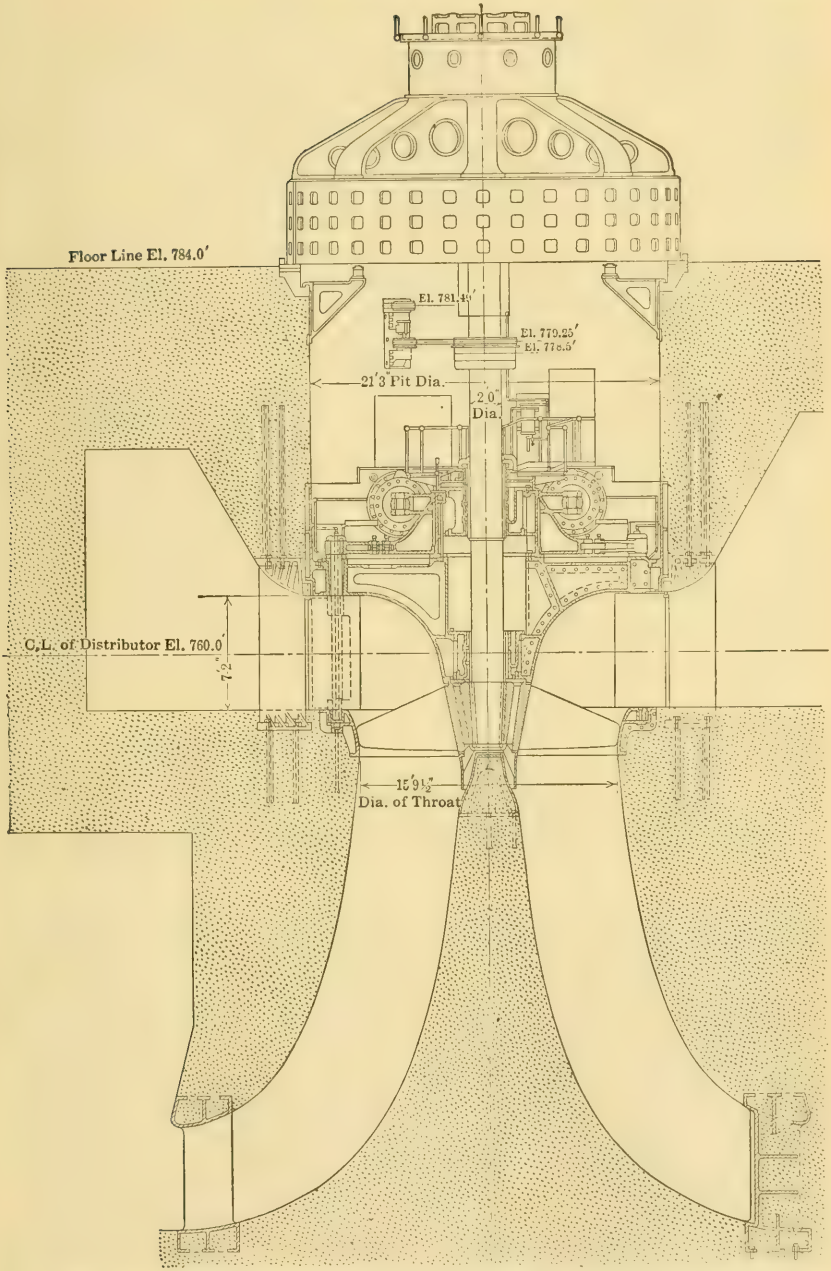


FIG. 137.—28,000 H.P., 138.5 R.P.M. I. P. Morris Turbine, Operating under 56 Ft. Head. Specific Speed, 153. Manitoba Power Development, Canada.

which causes the water to spread out in all directions. The bell-shaped mouth at the bottom of the vertical portion of the draft tube is so shaped that the area for the flow increases rapidly as the water approaches the edge of the flat plate. This produces a corresponding decrease in the velocity of the water, so that most of the discharge velocity is regained in the form of suction head on the wheel.

A careful investigation must also be made for each particular design of runner, to determine its proper location above the tailwater, so that the total vacuum at the top of the draft tube will not exceed the barometric column. The total vacuum at the throat of the runner is dependent not only on the static elevation above tailwater elevation, but also on the velocity head existing at this point. At sea level and a temperature of about 70° F., the barometric column is about 33 feet and for such conditions the total draft head, as determined by the following formula, should not greatly exceed 27 feet, since a certain margin between these two values must be maintained to allow for pressure changes due to the movement of the turbine gates for regulating purposes. For plants located at elevations above sea level, where the barometric column is less, the same margin should be allowed in determining the draft head.

$$h_d = s + \frac{v_1^2}{2g} - \frac{v_2^2}{2g} - \text{losses},$$

where h_d = total draft head in feet;

s = elevation of center of runner above tailwater, in feet;

v_1 = velocity of water through the runner in feet per second;

v_2 = discharge velocity from the draft tube in feet per second.

The possible location of the runner with respect to the tailwater is thus governed entirely by the total draft head on the unit. Since this head, as just stated, depends on both the height of the runner above tailwater and the velocity head at the discharge of the runner, it is evident that as the specific speed and velocity head for a given runner increase for a given head, the runner must be lowered. For the same reason, as the head increases for a specific speed, the elevation of the runner must also be lowered. When the modern high-speed propeller type of runner is used, it may thus be necessary to place it close to normal tailwater elevation. This may lead to an objection on the ground of inconvenience in gaining access to the runner for inspection during times of abnormal height of tailwater.

The probability of emergencies requiring the shutdown of the unit for examination or repair is, however, very slight in large modern instal-

lations, with the high class of design and workmanship now available. Moreover, in the propeller-type forms of high-speed turbines, when built in the large sizes of units now adapted, it is not necessary to provide a manhole for entrance to the draft tube below the runner, since this space is readily accessible through the wide openings between the runner blades. It is, therefore, possible in many plants to place the runners close to the normal tailwater elevation, without likelihood of any serious inconvenience.

It is also obvious that, should the development of the propeller type of runner continue to tend toward higher heads or higher specific speeds, conditions might arise in which it would even be necessary to locate the runner below tailwater. Such a location would require excessive excavation and, in addition, would be very inconvenient, as it would be practically impossible to get at the runner unless some means of unwatering the draft tube were provided. This has led to the suggestion, by H. B. Taylor of the I. P. Morris Company of the so-called inverted turbine, which is an ordinary turbine turned upside down, with the casing and runner placed at the bottom of the substructure, the draft tube discharging vertically above the runner.

The advantages of the new forms of draft tubes are therefore of greatest importance in high-specific-speed installations, since the discharge from the runners has such a large velocity head compared to the head of the plant. A draft tube of very high efficiency is therefore essential. With high-head plants and low specific speeds, the draft tube is of less importance, as far as efficiency is concerned, but a defective form of tube is very objectionable in any case, on account of its liability to dangerous vibrations, as well as poor part-gate efficiency and poor over-gate conditions.

The draft tubes are generally molded directly in the concrete substructure. The upper section, immediately below the runner, is however often made of cast iron in sections, and so arranged that they can be lowered to facilitate the removal of the runner from below, thus dispensing with the necessity of dismantling the generator. If the shaft is made hollow, the power-house crane can also be used in handling the runner. Tunnels with tracks leading directly to these locations where the runners can be removed have been provided in some of the larger installations, and naturally greatly facilitate the work.

Shaft and Bearings. With horizontal units, separate shafts are almost always provided for the turbine and the generator, the two being bolted together by a coupling. The generator bearing nearest the turbine often has to support the turbine runner at this end, and this additional weight, as well as the water thrust, must be given due con-

sideration. Where a separate flywheel is added between the turbine and the generator, it may be found necessary to provide bearings on either side of this, in which case four bearings would be required for the whole unit. Most bearings of horizontal turbines are of the ordinary oil-lubricated, babbitted type, except in the older submerged designs, where lignum-vitae bearings had to be used.

With vertical units, it is also customary to provide separate shafts for the generator and the turbine, with forged-flange couplings for bolting together. Where the two units are located very close together, a one-piece shaft may be desirable. The end of the turbine shaft is usually tapered and fitted into the hub of the runner.

For supporting the revolving element of vertical units a common thrust bearing is now always used. As described more fully under *generators*, page 331, this is almost always located on the bearing bracket above the generator, and the generating unit also provides for the upper and often an intermediate, babbitted, oil-lubricated guide bearing. The lower guide bearing, which forms part of the turbine, is a water-lubricated lignum-vitae bearing, located in the turbine-head cover close to the runner. The bearing shell may be split both horizontally and vertically, to facilitate the removal.

The lignum-vitae is dovetailed into the bearing boxes in the form of strips running parallel to the axis of the shaft, and with the end grain of the wood placed normally to the surface of the shaft. Twenty or more of these strips, evenly spaced in a liberal length and separated by spaces for circulation of cooling water, are so proportioned as to present sufficient area to the shaft to insure very satisfactory performance.

In the case of turbines operated in clear water, the supply for the bearing may be taken through a pipe directly from the wheel-casing (Fig. 138). A duplex strainer should be connected in the line to remove any foreign substances which might otherwise reach the bearing and damage it. In installations in which the water carries large quantities of foreign matter in suspension, a suitable central filtering system should be provided. As a precaution, in case the lubricating water supply should become clogged, an indicator and alarm bell or light can be installed to warn the operator that the bearing is not being properly lubricated.

Impulse Type. Like the reaction type, impulse turbines are built in many different designs, the controlling factors differing so materially in each installation that they not only affect the general type or arrangement of the design, but also of details.

Horizontal and Vertical Wheels. Impulse turbines are almost exclusively of the horizontal type. This not only represents the most

economical design, but it has many advantages of simplicity of construction and arrangement of parts available for inspection, lubrication, and cleaning. Vertical wheels have been built, however, and operate satisfactorily, and they may be used for comparatively low-head plants, where the water contains large quantities of sand or grit. With this type, up to six jets can be installed in a single-wheel runner.

Runners. There are two general types of wheel-runners, the double-lug bucket type and the chain or triple-lug bucket type. In the former, the wheel center consists of a single rim and the buckets have two lugs which are machined to a press fit over the rim of the wheel center and

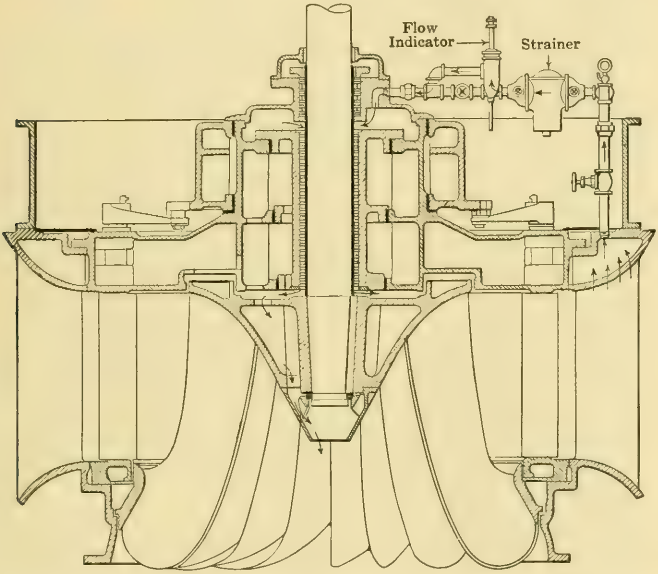


FIG. 138.—Section through Vertical Turbine and Lignum-Vitae Bearing Lubricated with Water.

held in position by two blots. In the latter type, a double or U-shaped wheel rim is required, and the buckets have three lugs, a forward center lug and two rear lugs. The forward center lug is a close fit between the two rims forming the duplex wheel center, and the two rear lugs straddle the rims, the arrangement of the lugs being so designed that the rear lugs of one bucket come directly in line with the forward lug of the next following bucket. A single bolt, therefore, passes through the rear lugs of one bucket, the rims and the central or forward lug of the next following bucket, thus connecting up all of the buckets into a continuous chain.

In the chain-type wheel, the base line of the buckets, or the distance between the supporting bolts, is very much greater than it is with double-lug buckets. This type of construction is, therefore, particularly suitable for all installations where the ratio between the diameter of the jet and the pitch diameter of the wheel is small, that is, where a large diameter of jet is applied to a comparatively small diameter of wheel. This is always the case where a very large power output is required, with a turning speed comparatively high, as proportional to the head of water, thus calling for large buckets on a comparatively small wheel. It is also especially suitable for extreme cases of large horsepower and high heads, making the wheel runner of the most stable construction.

The buckets are ellipsoidal, which causes the water jet to impinge without shock or disturbance, and it is discharged along natural lines over the entire bucket surface. The central portion of the front entering wedge, or lip, of the bucket is cut away in the form of a semicircular notch, and this opening allows the solid circular water jet to discharge upon the central dividing wedge of the bucket without being split in a horizontal plane, with the result that all eddy currents are avoided and the full force of the jet is expended for useful work, resulting in the maximum bucket efficiency.

Figure 139 shows one of the impulse wheels for the 30,000 H.P. units in the Caribou plant of the Great Western Power Company. These wheels operate under a head of 1008 feet, at a speed of 171 R.P.M. Each unit consists of two wheels, one on each side of the generator. Each bucket is 36 inches wide and weighs 1000 pounds.

Arrangement of Runners. The two principal runner arrangements are the single-overhung and the double-overhung. The earlier direct-connected units were of the coupled type, the wheel being self-contained with its own shaft, bearings, base, and housing, and being connected to the generator by a coupling, either flexible or rigid. Both wheel and generator were usually mounted on the same sub-base, and where more than one runner was required these were mounted on the same shaft and in the same housing. In this country, the coupled type is now used only for small units, although abroad it is still employed occasionally for large turbines.

For practically all large units, as well as for many small ones, the two-bearing type of construction with overhung runner is used, the generator rotor being mounted between the two bearings, and the runner overhung on the extended end of the shaft bearing (Figs. 123 and 140). This type of wheel is extremely compact, the entire unit being self-aligning, and the windage, friction and other mechanical

losses being reduced to a minimum. It is the ideal construction for large units, and is extensively used. With the double overhung type, it is possible to make a prime mover of double the power output, maintaining the same speed of rotation with the same conditions of water pressure. In some instances, three and even four runners drive

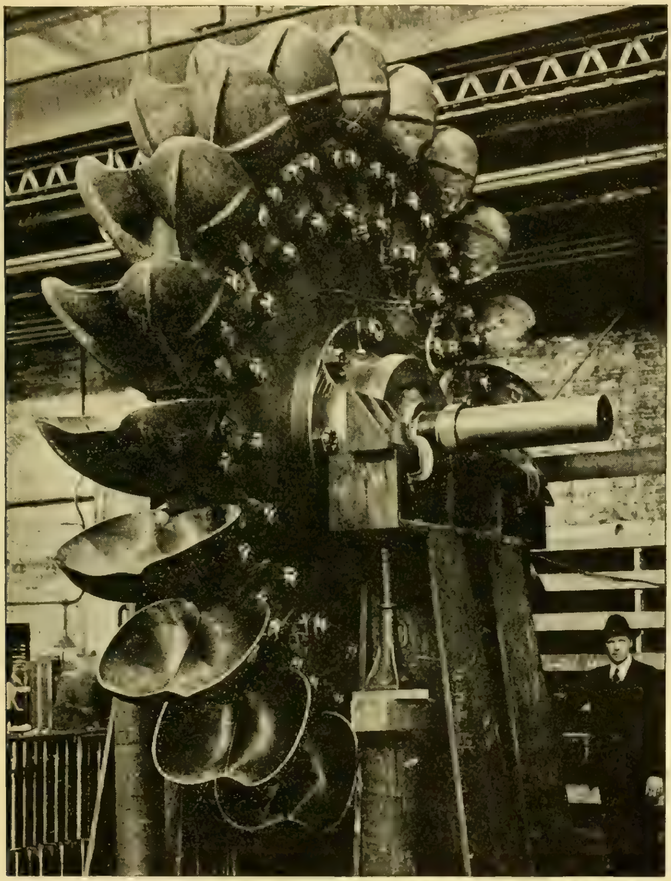


FIG. 139.—One of the Two Impulse Wheels for the 30,000 H.P. Units in the Caribou Plant of the Great Western Power Company. (Built by the Allis-Chalmers Company.)

the same generator. Where four runners are used, four bearings are usually required, the generator rotor being mounted between the two main bearings with an outboard bearing at each end, two wheels being located between one main bearing and one outboard bearing. At the present time, however, a reaction turbine is likely to be selected for

conditions that a few years ago would have seemed to call for multiple-runner impulse wheels.

Referring again to Fig. 123, a water connection for throwing a fine spray of water through the hollow shaft will be noted on the outer end of the right bearing. Within the housing of a tangential wheel there is a very definite vacuum, due to the action of the revolving wheel as a centrifugal blower and the action of the jet of water as an injector. Therefore, a fine spray of water is discharged into the open end of the shaft and drawn through, and is most effective in cooling.

The illustration (Fig. 123), also shows what is termed a "tailrace

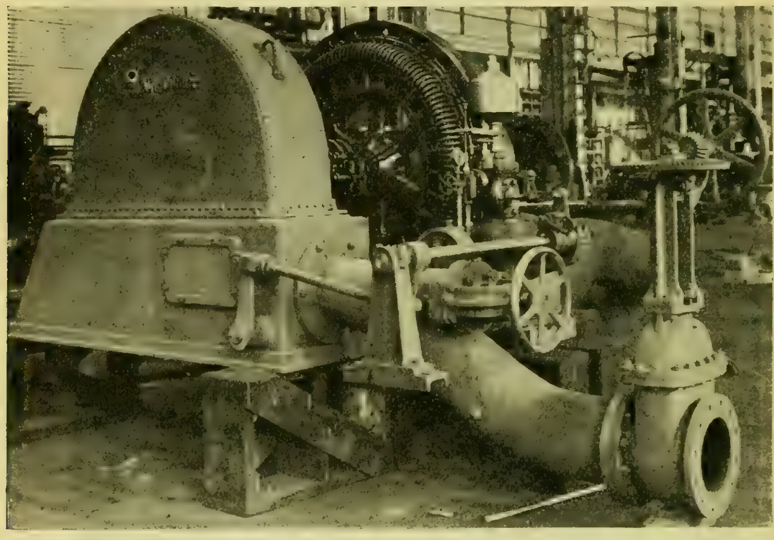


FIG. 140.—Single Overhung Impulse Turbine, Governor Regulated by Jet Deflector. (Built by Pelton Water Wheel Company.)

ventilator." This is a labyrinth passage from the bottom of the generator pit to the water-wheel pit, the vacuum existing in the water-wheel pit bringing about a very definite circulation of air which it draws out of the bottom of the generator pit.

Nozzles. The two principal types of nozzles used with impulse turbines were described under "Speed Regulation," page 218. While one jet per wheel is used in most cases, there may be installations where the head of water available is low, as compared with the quantity of water, and where it is desired to maintain a comparatively high speed of rotation. Under such conditions two jets of water may be applied to each wheel from the same nozzle body, the jets being approximately 60° apart. Such an arrangement is shown in Fig. 141.

Housings. The general type and construction of wheel-housings or casings for impulse turbines is illustrated in Fig. 140, the best practice being to provide a separate housing for each wheel to prevent interference from discharged water. The lower part is usually made of iron castings and the upper housing or cover of steel plate riveted into a cast-iron frame. This type of housing for large units is claimed to be preferable to a housing made entirely of cast iron, as it is lighter to handle and eliminates any danger of breakage where the shaft of the

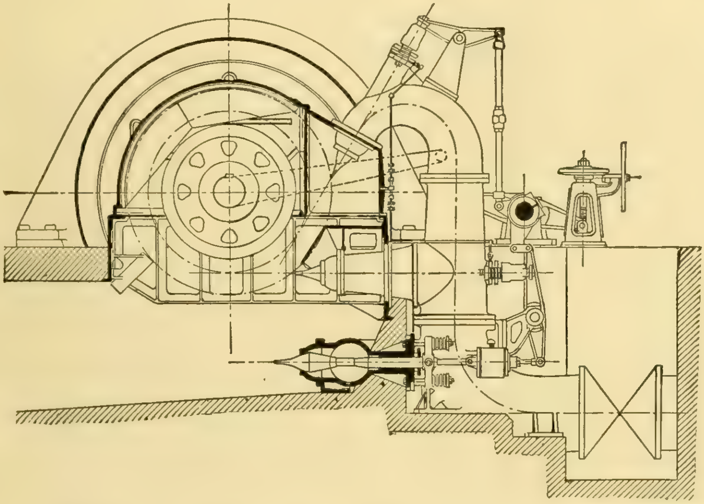


FIG. 141.—Impulse Turbine with Two Nozzles per Wheel. Arranged with Auxiliary Relief.

runner passes through the sides of the housing, and water leakage is prevented by means of a centrifugal disc and water guard, a device which insures a frictionless packing. For small units, on the other hand, the self-contained cast-iron housing is, as previously stated, to be preferred.

2. GOVERNORS

In the early days of hydro-electric developments, it was considered advantageous, and in many cases even necessary, that governors should be capable of a very close speed control. The reason for this was partly the wide fluctuations in the load and also the inadequate flywheel effect in the turbo-generator units. At the present time, however, particularly with our large interconnected systems, the ordinary load changes are of relatively small percentage, more flywheel

effect is being provided for, and considerable benefit results from the flywheel effects contained in the load itself.

With most modern systems, a very moderate rate of gate operation will meet ordinary requirements, especially if each governor does its share of the regulation. The necessity for a high rate of gate movement arises only when large blocks of load are cut off by line troubles, etc. Even under such conditions, less rise in speed may be expected if the more liberal flywheel effect is included in the units; and, owing to the general use of automatic voltage regulators, reasonable changes in speed have no appreciable effect on the voltage.

Factors Affecting Speed Regulation.[1] While the regulation of speed originates with the governor, it also involves a consideration of the pipe-line conditions and those devices required for limiting the pressure rise therein, besides the flywheel effect of the rotating elements of the generator and water wheel, as mentioned above.

Variations in the velocity of the water in the pipe line will always occur, and every retardation in velocity of the moving water column will bring about an increase in the pressure, in inverse proportion to the time occupied for a given change. It is thus evident that the quicker the governor movement, the greater the pressure rise will be, while, if the governor movement is made slower, the speed increase will be greater, and a proper balance between the two determines the correct time for adjusting the governor closing stroke. It is also evident that the greater the inertia of the rotating masses, and the higher their rotation, the smaller the speed variation will be. A sufficient rotating mass to supply stored energy (WR^2) must, therefore, also be introduced to keep the speed within permissible limits.

To secure a constant speed with a water wheel operated under a variable load, the energy produced by the water wheel must be varied proportionally to the load, and the method of achieving this in practice, except for tangential impulse wheels with by-pass nozzles, consists essentially of varying the size of the gate openings through which the water to the wheels is admitted (see " Speed Regulation," page 217).

The regulation of hydro-electric units requires a certain departure from normal speed before the governor can act. Since the immediate effect of the gate motion is opposite to that intended, the speed will depart still further from the normal, which, in turn, tends to cause the governor to move the gate too far, with the result that the speed will not only return to normal as soon as the inertia of the water and the rotating parts is overcome, but may rush far beyond normal in the opposite direction.

[1] See also "Pipe Lines," "Waterhammer and Surge Tanks."

A given gate opening will produce a certain velocity of the water in the penstock, and the energy of the moving water will be equal to the weight of the water in the penstock multiplied by the square of the velocity and dividing this product by 64.4. For example, with a penstock 300 feet long and 6 feet in diameter, the weight of the water would be 530,000 pounds, and, assuming a velocity of 5 feet per second, corresponding to the head and full gate opening, the total kinetic energy of the water would be

$$\frac{530{,}000 \times 5^2}{64.4} = 205{,}752 \text{ foot-pounds.}$$

If the gates are now instantly closed to about one-quarter gate opening, so that the velocity would be reduced to 1.5 feet per second, the corresponding kinetic energy would only be 18,517 foot-pounds. The loss of energy is, therefore, equal to 205,752 − 18,517 foot-pounds, and this amount will be transferred to the water issuing from the gate apertures, which, therefore, will have its velocity increased until the 187,235 foot-pounds of energy has been absorbed. The kinetic energy of the water column will, therefore, be transferred to the water wheel at the very moment when it is desired to reduce the energy produced by the wheel. In the same manner, if the load be thrown on and the gate again instantly opened full, the same amount of energy which the water column gave out on being retarded in the previous case will be absorbed by the water column in accelerating its velocity to 5 feet per second. The energy delivered to the wheel will, therefore, be reduced, causing its speed to drop off, just when the opposite is required, and this action cannot be overcome by rapid movement of the gate, but, on the contrary, is intensified by more rapid gate movement. It is, therefore, obvious that after the governor has been set in motion by a change of speed, some means, other than the return of the speed, must be provided to stop it when it has moved the gates the amount required by the change of load which was the cause of the change in speed that originally set the governor in motion. The means provided for this purpose is known as the " compensating " mechanism, and is an essential feature of all quick-acting water-wheel governors.

It is a comparatively easy matter to calculate the speed-regulation in cases where the inertia of the moving water column is a negligible quantity, as with open flumes and short draft-tubes. For such conditions, the following formula applies:

$$d = \frac{800{,}000 \times \text{H.P.} \times t}{WR^2 \times n^2},$$

Where d = ratio of increase or decrease in speed;
H.P. = horse-power suddenly thrown on or off;
t = time for the movement of the gates in seconds;
WR^2 = weight of the rotating parts multiplied by the square of the radius of gyration; i.e., the flywheel effect;
n = normal speed in R.P.M.

For installations with long penstocks, the regulation becomes much more serious and is difficult to calculate accurately, owing to the many variable factors involved, such as the length of the pipe line, the effective head and velocity of flow, time of governor action, flywheel effect and effect of standpipes, etc.

The final speed after a load change will be that due to the initial kinetic energy of the rotating parts and the excess or deficiency above or below the load requirements during the time of gate adjustment. This excess or deficient energy is due to the excess or deficiency in the quantity of water during the change, in addition to that of the energy required to accelerate or retard the water column in the penstock.

The effect of a standpipe must also be considered in absorbing the excess power. When such a structure of sufficient size is installed close to the wheels, the conditions will approach those of an open flume, while, if it is located some distance from the plant, they become similar to those of a closed penstock of a length equal to the distance from the draft-tube to the standpipe.

No general rule can be given for the rate at which the governors should open or close the gates. It can be more rapid the shorter the penstock and the lower the velocity of the water. The effect of both rapid opening and closing of the gates should be investigated in every projected plant, in order to guard against drawing down the pressure at critical points in the penstock below that of the atmosphere, and thereby causing danger of collapse, or permitting increases of pressure beyond the strength of the penstock. A moderate rate will generally be sufficient for most cases, the usual operating time to move the gates over the full range for full load thrown off being from $1\frac{1}{2}$ to 2 seconds for medium size turbines, while for larger units it may be 3 to 4 seconds.

Figure 142 shows two typical speed-change curves for various percentage load changes. These curves assume the shortest possible penstocks or practically open water conditions, and only one unit operating on rheostatic load. The fly-wheel effect, WR^2 in either case is assumed to be approximately 3,000,000 and the governor action, i.e., the time required for the governor to move the water-wheel gates through their entire range, 2 seconds for Curve A and 4 seconds for Curve B.

It will be noted that Curve *A*, which represents the most conservative American practice, with 2-second governor action, gives a speed increase of 25 per cent for full-load change. In general, Curve *B*, using 4-second operation, should be satisfactory. Shorter time of operation could be used when only one or two units were installed, and increased later as additional units were put into operation. With large installations, when the plant is carrying a large portion of motor load, Curve *B* would flatten out until it approached or even crossed Curve *A*.

Although the regulation is often specified for full-load change, it does not necessarily follow that this high value is objectionable, because, as previously mentioned, such a load change occurs very seldom in practice. When it occurs, it is due to some abnormal operating condi-

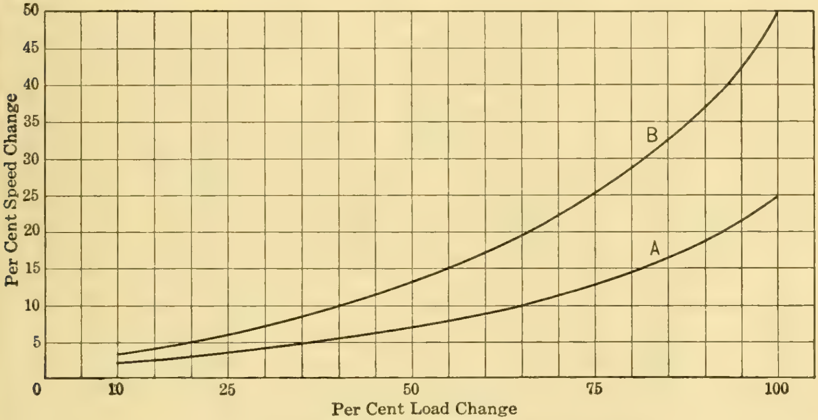


FIG. 142.—Typical Governor Speed-Change Curves.

tion; the generator is usually being disconnected from the system, and the automatic regulator will also tend to keep the voltage within a safe limit. On the other hand, a turbine with, say, a 50 per cent speed change for full-load change will only have a speed variation of about 5 or 6 per cent with a 25 per cent load change, which is entirely satisfactory.

Principles of Operation. The most important requirements of a speed governor are accuracy and promptness, and where two or more turbines drive synchronous generators in parallel, the speed which each governor will maintain should show a similar drooping characteristic from no load to full load. The movement of turbine gates requires a relatively large amount of energy and indirect-acting governors are therefore almost exclusively used, employing either mechanical energy, as with the so-called mechanical governor, or a compressed fluid as with the fluid-pressure governors.

Mechanical governors obtain their energy mechanically by belt drive from the prime mover and transmit it by friction couplings, etc., to the gate shaft. They are not very sensitive but exposed to considerable wear, for which reason they are only used for very small units. In fact, they are being rapidly discarded.

With the fluid-pressure type of governor, also known as the hydraulic type, the centrifugal element controls a pilot valve, and this in turn controls the operation of the hydraulic pistons or servo-motors, which operate the gates. In the smaller sizes of some makes of governors, the

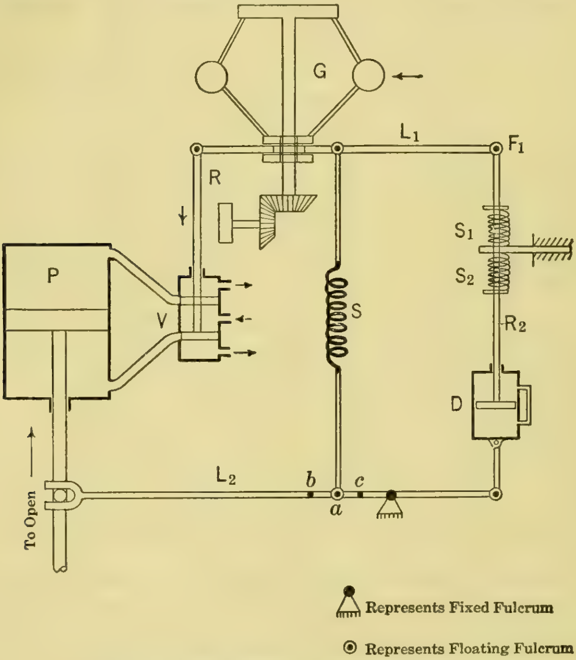


FIG. 143.—Elementary Governor Diagram.

pilot valve directly controls the operating pistons, but in most cases a so-called relay valve is interposed between the pilot valve and the pistons. This permits the use of a small well-balanced pilot valve, and imposes minimum duty on the centrifugal flyball element. Various hydraulic and mechanical schemes are used in different makes of fluid-pressure governors, but in all cases the ultimate result is to amplify and control the action of the centrifugal element.

The simple diagram, Fig. 143, and the following brief description as contributed by F. T. Coldwell, will serve to illustrate, in a general way, the principles involved in governor operation.

"G represents the centrifugal element, V the pilot control valve and P the gate operating piston. The spring S, which opposes the action of the centrifugal force, is arranged so that its tension is decreased as the gates open, thus giving the drooping speed characteristic required in most cases for parallel operation. A similar action is obtained to a greater or less degree, as may be required by the particular hydraulic conditions, the flywheel effect and the amount of load change involved, by the action of the *compensating mechanism.* This consists of the lever L_2, the dashpot D, and the centering springs S, and S_2, all arranged to control the position of the floating fulcrum F_1 of lever L_1.

"Small load changes on a system having adequate flywheel effect will be manifest by the speed falling at a correspondingly low rate. A small increase in load will thus cause the speed to decrease slowly, thus decreasing the centrifugal force, allowing S to move the valve rod R slowly downward. This causes the piston to move upward and open the gates, at the same time decreasing the tension of spring S, thus arresting the movement of the gates when the speed ceases to fall. Therefore, the rate of travel of the piston will be the same as the rate of travel of R, and the operation of the gates will be the same as if they were directly controlled by the centrifugal device, except for the amplification of the force obtained.

"With the slow rate of movement assumed, the downward force exerted by L_2 through the dashpot D will be less than the opposing force of spring S_1, the oil simply flowing around the by-pass connection. Therefore, the compensating mechanism will not appreciably change the position of fulcrum F_1 and the rate of movement will be determined entirely by the action of spring S. If the governor is designed for a 5 per cent decrease in sustained speed from zero load to sustained full load, a small change in load resulting in a decrease in speed at the rate of, say, $\frac{1}{2}$ per cent per second, will cause gate operation at the rate of full travel in 10 seconds, and so on.

"With greater changes in load, the rate of gate movement which might occur without the compensating device is not permissible. This is particularly true in case of unfavorable hydraulic conditions and with inadequate flywheel effect. For example, if, as previously mentioned, the turbine is supplied through a long closed penstock, a definite amount of stored energy is represented by the water moving at a velocity corresponding to a certain sustained load. If the load decreases, this stored energy must be expended, as it assumes a lower velocity, and vice versa. If the gate opening is suddenly decreased a considerable amount, the pressure at the turbine may rise, owing to the inertia of the water column; and the quick decrease in gate opening results in the

stored energy being used at a higher rate. That is to say, the immediate effects of the change in the gate opening may be opposite to the final effects.

"With load changes of greater magnitude, tending to cause a high rate of movement of piston P, the dashpot D will exert a downward force on the rod R_2 in proportion to the rate of gate movement. The movement of R_2 will be checked by an opposing force due to the compression of spring S_1, and fulcrum F_1 will therefore be displaced downward by an amount in proportion to the rate of gate movement. This will restore the valve rod R to its normal position, arresting the movement of the gates in advance of the restoration to normal conditions. The fulcrum F_1 is then returned to its normal position by spring S_1 in a certain time, which may correspond to the time it takes for the turbine to respond to the change in gate opening due to the new load condition.

"Sometimes it is desired to allow certain units to do the greater share of the regulating, while others are operated at a more constant load under normal conditions. This may be accomplished by decreasing the permanent drop effect in those governors which should be more active, and by increasing the drop effect and the compensating action in the governors which should maintain the more constant load. The drop effect may be changed, in the simple governor arrangement shown in Fig. 143 by changing the point of attachment of the spring S to lever L_2. For example, if the governor is set for a certain drop in speed from zero load to full load, with spring attached to lever at point A, the drop effect would be greater at b and less at c."

Pressure System. The energy for actuating the gate cylinder pistons of the turbine is obtained from a pressure system. This may be either of the individual or central type. The former is generally used for installations with one or two turbine units, in which case each unit is provided with its own pump, pressure and sump tank and necessary piping, valves and gauges.

The fluid which is used to operate the power cylinder of the governor is obtained from the pressure tank, which normally should be about half filled and of sufficient capacity to provide for a series of governor strokes, even though the pump be temporarily inoperative. The receiving tank receives the fluid after it has performed its work in the governor, the function of the pump being to draw the fluid from the receiving tank and force it into the pressure tank together with a sufficient amount of air to obtain a pressure of from 100 to 200 pounds per square inch. This compressed air is the immediate source of energy for operating the governor, and although the pump accumulates or

renews this energy at a comparatively slow rate, it is available for use in the governor as rapidly as the requirements of regulation demand. It is this principle which makes possible the rapid movement of the gates.

The central pressure system generally consists of two or three pumps located at one place in the station. One of these pumps is maintained for reserve, and the others must be of sufficient capacity to take care of the entire requirements of all the units. These pumps then discharge into a common pressure main running the entire length of the station and connected to a pressure tank for each unit. The discharge fluid from the governors is similarly conveyed through a common return main to a sump tank located near the pumps. With the central system the pumps are generally motor-driven. This method of drive may, of course, also be used with individual systems, although in such instances possibly the majority of pumps are belt-driven from the main unit, especially for smaller units.

The pressure fluid may be either oil or water, the latter now being used very extensively in large installations on account of its cheapness and cleanliness. It also permits the use of centrifugal pumps, which are not suitable for oil on account of the damaging effect of the churning. Oil is, however, still generally used in many plants, and in such cases, as well as for small units, the centrifugal pump is not so suitable, and rotary pumps are mostly used.

When water is used for pressure fluid it must, of course, be very clean and free from acids. It must also be treated to prevent corrosion of the piping and governor valves. Two methods are advocated for this, either being used with entire success in the larger hydraulic power stations of the country. The first method consists in adding to the water from 1 to $1\frac{1}{2}$ per cent of a soluble, light emulsion oil. This mixes thoroughly with the water and gives it sufficient lubricating qualities, while the pipes and valves are apparently given a light protective coating of oil on the inside. The second method consists in treating the water with potassium bichromate, this salt being added to the water in the governor system in the proportion, by weight of from 0.02 to 0.06 of 1 per cent. The bichromate does not seem to have any chemical action on the water, but produces a coating on the insides of the piping and valves which protects them from corrosive action.

Governor Arrangements. The rapid growth in size of units has brought about a corresponding change not only in the size of governors, but also in the arrangement. Standard governors were formerly self-contained; that is, the control and power elements were combined in the governor itself. It was necessary only to connect the centrifugal element to the turbine shaft and the power element to the turbine gate

mechanism. While this arrangement is still in use with small units, it is no longer used for large units. In the latter case the centrifugal control mechanism and regulating valves are now combined and localized in an " actuator " placed in any convenient position on the main floor near the unit, and the power element or servo-motor is incorporated in the design of the turbine proper. By separating these elements, it is possible to locate each of them in the most advantageous position with respect to the individual function it has to perform. In some installations the actuators have been placed directly above the regulating cylinders of the turbine (Fig. 144), being completely remote-

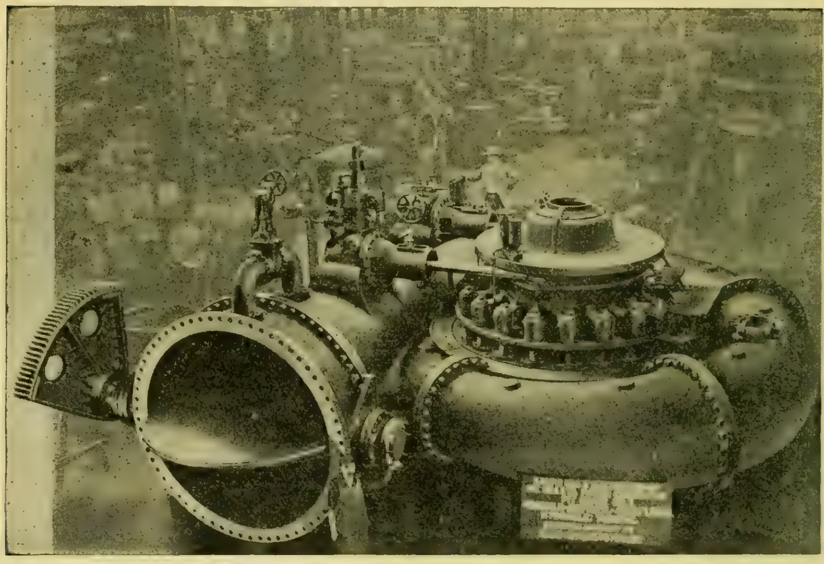


Fig. 144.—40,000 H.P., 275 R.P.M. Turbine. Pit River No. 1 Development of the Pacific Gas and Electric Company. Showing Integral Type of Governor and Pivot Valve. (Manufactured by the Allis-Chalmers Company.)

controlled from the switchboard. Another novel feature in governor design is the mounting of the centrifugal flyball mechanism directly on the vertical main shaft of the turbine, either above or below the rotor.

Methods of Control. Governors up to about 60,000 foot-pounds capacity are often equipped with mechanical hand control independent of the servo-motor. This is, however, scarcely feasible with larger governors on account of the time that would be required to develop so much power by hand. They are, therefore, equipped with hand control of the operating pressure only. This control is independent of the

centrifugal speed element, and is of great value for adjusting the load on the unit and for synchronizing purposes. In addition to local hand control, all governors are now, as a rule, equipped with manual remote control. The mechanism is equipped with a small reversible motor electrically connected with a double-throw control switch on the switchboard, and enables the operator to control the load and speed from the switchboard.

Numerous plants can be found where the units must first be paralleled by hand and the governor " cut in " after the generators are

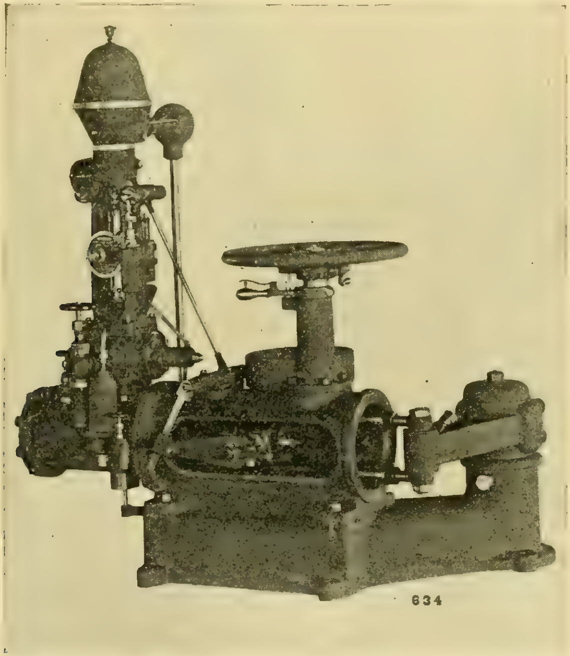


Fig. 145.—Type H.R. Horizontal Relay Valve Oil Pressure Governor. (Manufactured by Woodward Governor Company.)

tied into the power system. The reason may be found in the lack of harmony of flywheel effect, the velocity of the water and the length of the pipe line.

Sometimes it is required to carry a fixed load irrespective of the load or speed variation of the system, and such fixed loads may be less than that developed at full gate opening. This requirement necessitates the use of a load-limiting device, which prevents the distributor of the regulating valve from attaining a position beyond the amount desired. A load-limiting device also allows of an adjustment according

to the head or quantity of water available at various times, and it should preferably have remote control.

Governor Capacity. The force necessary to open or close the gates must be sufficient to overcome the water pressure and the friction of the mechanism. The gates always have an unbalanced moment, due to a difference in water pressure on the two sides, and this unbalancing is usually greatest in the closed position.

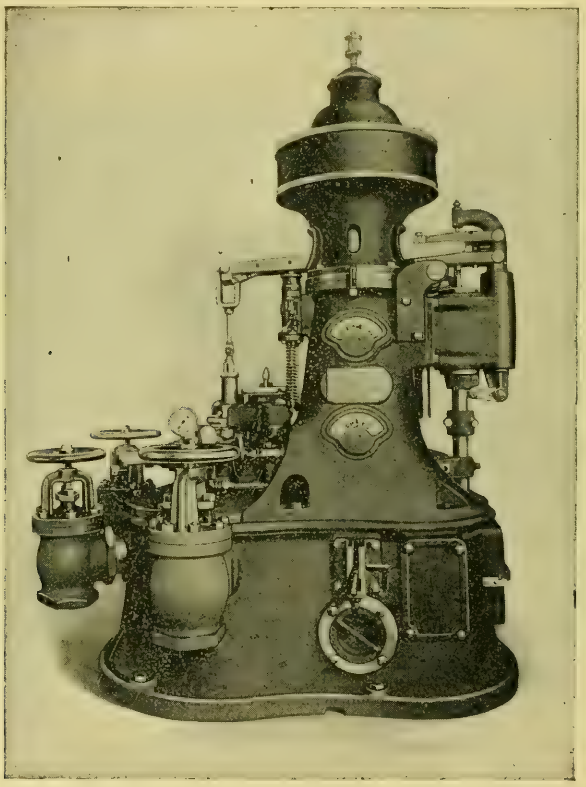


Fig. 146.—Type W Governor. (Manufactured by Lombard Governor Company.)

Governors are usually rated according to the foot-pounds of energy which the operating cylinders are capable of exerting. It is the product of the force on these cylinder pistons at a certain pressure, usually 200 pounds per square inch, times the stroke in feet.

The following formula as given by W. R. Kepler in the *Electric Journal* for February, 1922, may be used for determining approximately the foot-pounds rating of the governor:

$$\text{Foot-pounds} = \frac{\text{H.P.}}{\sqrt{H}} \times k,$$

where H.P. = Horse-power rating of turbine;
H = Head in feet.

For heads below 45 feet, $k = 50$ to 60;
For heads up to 200 feet, $k = 40$ to 50;
For high heads $k = 35$ to 45.
In general, the capacity is taken as:

$$\frac{\text{H.P.}_{\text{(max)}}}{\sqrt{H}} \times 50,$$

being the rating at 200 pounds per square inch.

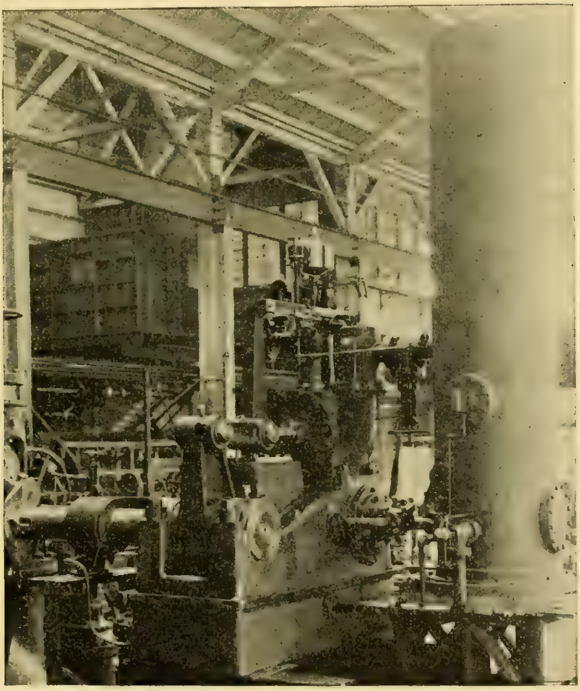


Fig. 147.—Type O-40 Governor and Pressure Tank. (Built by Pelton Water-Wheel Co.)

Typical Designs. A description of the many governors on the market and their operation can readily be obtained from trade catalogues and will not be gone into here. Figures 145 to 147 illustrate typical designs.

3. PRESSURE REGULATORS AND RELIEF VALVES

It has previously been explained that excessive pressure rises are liable to be produced in long pipe lines by a rapid closing of the turbine gates. To prevent such surges, the operating time must be made slower, and it is therefore necessary to use a large flywheel effect to maintain a reasonable speed regulation; otherwise a surge tank must be placed close to the power-house to shorten the effective length of the pipe line. If neither of these arrangements is practical, some other means must be provided, such as pressure regulators and relief valves.

Pressure Regulators. These operate in synchronism with the turbine governor and become immediately operative with the closing gate motion, and this action continues until the gates stop moving. The water rejected by the turbine as the gates close is discharged through the regulator. Thus the penstock velocity, instead of being suddenly checked, resulting in waterhammer, remains practically unchanged. The device is made water-saving by the use of a dashpot, which permits a relative motion of the connection between the turbine gate mechanism and the by-pass valve. The adjustment of the dashpot is such that the by-pass, after having been opened by a sudden closing of the turbine gates, is closed within a period which is sufficiently long to prevent a dangerous pressure rise in the pipe line. If the load goes off gradually and the gates are closed at a rate slower than that produced by the dashpot, the pressure regulator remains inactive. If the gates are again opened before the dashpot has closed the pressure regulator, then it should close synchronously with the gate motion; otherwise an excess quantity of water is discharged, causing a drop of pressure in the pipe line.

In order to obtain ideal results, the maximum capacity of the regulator should be equal to the full-load discharge of the turbine less the discharge required to run at synchronous speed without load. Ordinarily, some sacrifice is made to reduce the size of the regulators. They are seldom installed in excess of 75 per cent of the maximum turbine discharge, and in many cases not more than 40 per cent or 50 per cent is provided. In such cases, of course, some pressure rise occurs in the penstock. The size of regulator depends largely upon the water velocity in the penstock and upon the length of penstock between the turbine and the forebay or between the turbine and the surge tank, if one is used. It is usually attached directly to the turbine casing and discharges into the tailrace, and the discharge should not be connected to the draft tube.

Figure 148 illustrates a governor-operated pressure regulator used

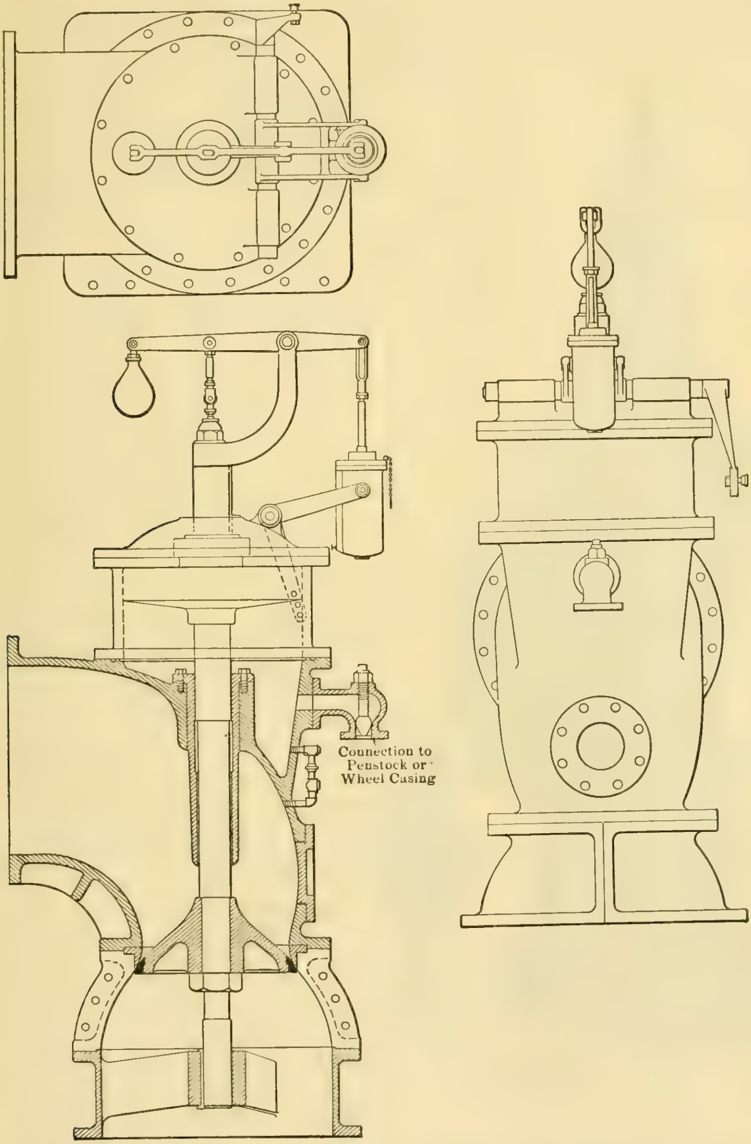


Fig. 148.—Governor-operated Relief Valve. (Wellman-Seaver-Morgan Company.)

with reaction turbines. It is mechanically connected to the gate mechanism of the turbine, but the power required to operate it is supplied by the pressure in the penstock. No load is imposed upon the governor nor any pressure drawn from the governor system. The connection to the turbine gate mechanism simply operates the pilot valve of the regulator which controls its action.

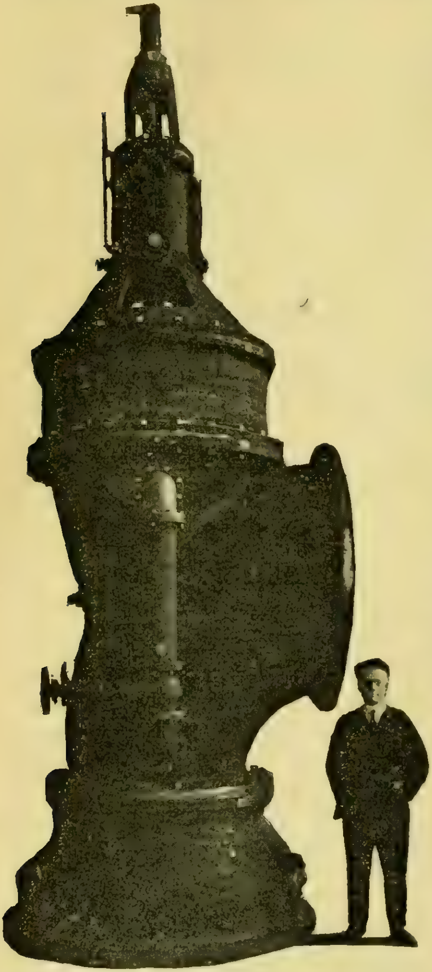


FIG. 149.—Governor-operated Relief Valve. (I. P. Morris Company.)

Figure 149 shows another type of governor-operated relief valve, in which the valve is interconnected with the turbine gates through a self-contained oil-pressure system, the operation of the relief valve being produced directly by the motion of the turbine gate. Above the elbow forming the body of the relief valve casing will be noticed a large cylinder containing a balancing piston, the purpose of which is to equalize the load on the valve, allowing, however, a small residual force tending to close the relief valve. Above the balancing cylinder is a smaller cylinder containing a piston for operating the valve. The two pipe connections shown at the ends of this small cylinder are joined by pipes to the two ends of a jack cylinder mounted on the tailrod on one of the operating cylinders of the turbine. The jack cylinder and the operating cylinder of the relief valve displace equal volumes when their respective pistons move through the full stroke. The relief-valve is thus forced to move by an incompressible fluid column, and the operation is similar to that which would be obtained by a direct mechanical connection between the turbine gates and the relief valve.

The slow-closing feature of the valve operation is obtained by by-pass connections joining the two ends of the operating cylinder. A needle valve permits the rate of closing to be adjusted. The method of operating this relief valve has several advantages. One of these is the positive action obtained, the effect of which is to prevent the turbine gates moving at a rapid rate, if for any reason the relief valve should fail to move owing to any accidental cause, such as lodging of obstructions in the relief valve. Thus, if the relief valve is unable to open, the turbine gates will be automatically prevented from closing, except at a slow rate which will not endanger the penstock.

Relief Valves. These are usually direct-pressure operated and do not act until the pressure in the pipe line or turbine casing has risen above normal. They are, therefore, a more direct means of protecting pipe lines against dangerous pressure rises, such as caused by the clogging up of the gates, etc. Figure 150 shows diagrammatically the design and arrangement of the Johnson relief valve. It is of the well-known needle type with the plunger 9 pointing towards the source of pressure. A tank 2 with sight gauge 3 is placed as close as possible to the valve and connected to chamber *A* by a short passage of liberal size provided with a check valve 4 having a small aperture 5 in the disc. This check valve permits free flow from chamber *A* to the tank but restricts the flow from the tank to chamber *A* and prevents the relief valve from closing too quickly. The tank has also a small pipe connection 6 leading to the pipe line. The valve is provided with a second port 7 which is connected to the conduit at a point where the pressure does not drop materially when the valve is opened.

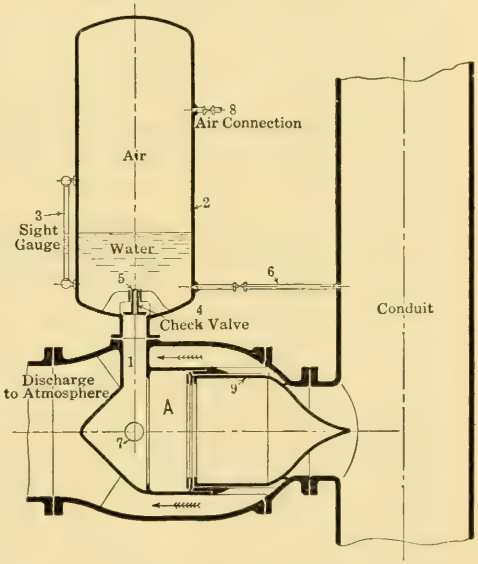


Fig. 150.—Johnson Relief Valve.

The relief valve is set by opening the valve in connection 7, admitting pipe line pressure to chamber *A*. This closes plunger 9 and holds it closed because the area of chamber *A* is greater than that part of the

area of plunger 9 which is exposed to pipe line pressure. At the same time, the air in tank 2 is compressed and the water rises to a certain level in the tank. This level is then adjusted to give a suitable volume of air, either by pumping in more air with a hand pump or letting air out through the vent, as the case may require. The volume of air in the tank is shown by gauge 3, and when once adjusted it will require only infrequent attention because it cannot escape unless the tank leaks or air is absorbed by the water in the tank. Leakage of water through the packing on plunger 9 is supplied by pipe 6 and does not affect the volume of air contained in tank 2. After plunger 9 has been closed, connection 7 is closed and the relief valve is ready to function.

The ratio of the area of chamber A to the area of the plunger seat determines the increase of pressure in the pipe line necessary to open the valve. These areas must be made to suit the conditions prescribed. If, for example, the valve is to open when the pressure increases 25 per cent above normal, then the area of chamber A should be 25 per cent greater than the area of the plunger seat. When so proportioned, an increase of more than 25 per cent in the pipe line pressure would overbalance the pressure in chamber A and the plunger would immediately open, discharging the water displaced from chamber A into tank 2. The pressure in chamber A does not increase when the pipe line pressure increases suddenly, because the small flow of water through pipe 6 is not sufficient to increase the air pressure in the tank in the short time interval under consideration.

It is obvious that the percentage of pressure rise necessary to actuate the relief valve will be maintained regardless of slow pressure fluctuations in the pipe line, because fluctuations which occur slowly are communicated to chamber A through pipe 6.

The Johnson relief valve is instantaneous in its action because it is held closed by a perfectly elastic medium, and the moving element, which is free from friction and inertia, is acted upon directly by the pressure which it is intended to relieve. The air pressure in tank 2 increases slightly when plunger 9 opens, but this increase may be minimized to any desired extent by making the tank larger.

For relief valves used with impulse wheels see section on "Turbines," page 218.

4. WATER-FLOW METERS

One of the most convenient means of measuring the amount of water taken by a hydraulic station, and for ascertaining the efficiency of the turbines, is the Venturi meter.

Venturi Meter. This consists of a meter tube, which is inserted in the pipe line as if it were a section of pipe, and of a register which is piped to the tube and which can be located at any convenient place in the station, as shown in Fig. 151.

The interior contour of the meter tube is shown in Fig. 152, and the

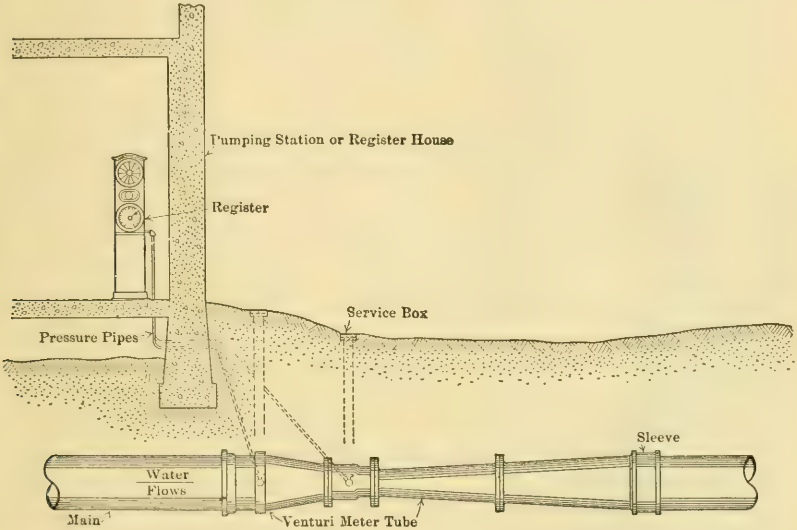


FIG. 151.—Method of Installing Venturi Meter.

accuracy of the meter greatly depends upon its proper design. As the water flows from A toward the throat B, its velocity rapidly increases and the pressure at B becomes materially less than the pressure at A. This difference in pressure between A and B can be accurately measured, and bears an exact ratio at all times to the rate of flow through the throat B. After passing the throat, the velocity begins to decrease with

FIG. 152.—Principles of Venturi Meter Tube.

an accompanying rise in pressure, and when C is reached the pressure temporarily lost at B has been almost entirely regained. Therefore, a properly proportioned tube not only provides a basis for accurate measurement of the flow, but will deliver practically the same amount of water as a straight pipe of equal length and diameter.

Commercial tubes are made in two or more sections, as seen from

Fig. 151. Near the inlet and at the throat are annular chambers communicating with the interior of the pipe by numerous ventholes. The throat portion is lined with bronze accurately bored to a definite diameter and contour.

Connections to the registering instrument are made by two small pipes, one at the inlet pressure chamber and the other at the throat pressure chamber. No water flows through these pipes, as they simply transmit the two pressures, the difference in which controls the readings of the instrument.

Registers. There are different kinds of registers, the most complete being illustrated by Fig. 153. At the back there are two vertical wells connected at the bottom. One well is subjected to the inlet and the other to the throat pressure of the Venturi Meter Tube, these pressures being transmitted by the two small pipes previously mentioned. In one well is a heavy metal float resting upon the mercury, a part of which flows from this well to the other well in direct proportion to the changes in flow through the Venturi Meter Tube. This is accomplished by giving the receiving well a variable cross-section. Consequently, the large float descends in direct proportion to the change in rate of flow, and its motion is transferred to the main shaft of the instrument by means of a rigid float rod and suitable gearing. The movement of the shaft is in turn transferred by means of rack-and-spur gearing to the long main lever of the instrument which carries the chart pen and the integrating counter.

Fig. 153.—Venturi Meter Register.

The recorder dial contains a large circular chart giving an unbroken autographic record of the rate of flow through the meter tube.

The counter dial shows the total amount of water (gallons, cubic feet, etc.) which has passed through the tube.

The indicator shows the exact rate of flow in gallons per day or other units at the moment of observation.

Where the expense of installing a complete registering outfit is prohibitive, or for testing the accuracy of register instruments, the manom-

eter may be advantageously used, and it may be connected with the same pipes that serve to connect the tube with the registering apparatus.

Manometer. The Venturi Meter Manometer as illustrated in Fig. 154, consists essentially of a U-tube using the same principle as a barometer. The large mercury well is connected to the upstream of the Venturi Meter Tube, and the throat of the Venturi Meter Tube is connected to the small vertical glass tube; thus the downward motion of the mercury surface in the mercury well is very slight in comparison with the upward motion of the mercury surface in the small glass tube. The slight motion of the large surface is properly corrected in the fixed scales of the instrument. The rate of flow corresponding to the difference in height of the mercury surfaces is read on the graduated scale. This instrument is absolutely accurate, containing no moving parts whatever except the mercury itself.

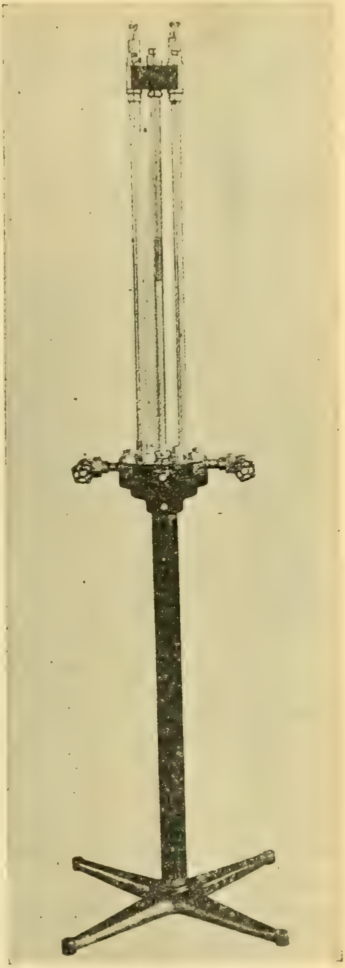


FIG. 154.—Barometric Venturi Manometer.

5. WATER-STAGE REGISTERS

Automatic water-stage registers are divided into two classes—those making a printed record, and those making a graphic record. In the first type a printed record of the gauge height and time is made, while in the second type the record is traced by a pen or pencil on the surface of a paper sheet, both moving in harmony with time and height.

The first type of register is designed to give printed records of the rise and fall of water continuously for a long period of time. It is especially adapted for use in inaccessible stations which it is difficult or impossible for the observer to visit frequently, and for which a continuous record is desired. The records are given at intervals of fifteen or thirty minutes.

Figure 155 shows an automatic water-stage register which makes a printed record, and Fig. 156 shows a tape reel for handling and examining the records. A graphic recording register is shown in Fig. 157.

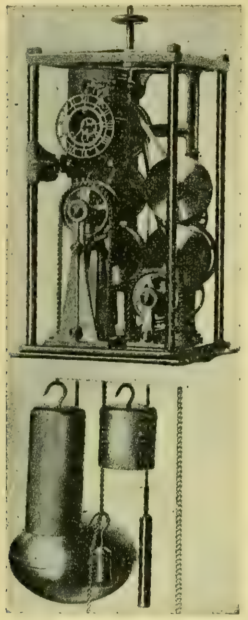


Fig. 155.—Automatic Stage Register Making Printed Record. (Manufactured by W. & L. E. Gurley, Troy, N. Y.)

An instrument has also been developed which telegraphs the gauge record from the pond, river, canal or lake, to some central point where the chief operator or control engineer may have available a continuous record of changes in water-surface elevations. The sender may be attached to a regular graphic water-stage recorder at the river, for example, and the record made at this point may be transmitted to an indicator or recorder in the power plant, or to a recorder in the office of the superintendent and to an indicator in the power station.

Another type of water-level indicator is that of the Selsyn system, by means of which reliable and accurate indications of a moving float device are instantly communicated to a remote observation point. It is based on the same principle of operation as the signal system described on page 614, and is the system in use for recording all the movements in the operation of the Panama Canal.

It consists of a so-called Selsyn generator and a Selsyn motor, so constructed and interconnected that every angular movement of the generator rotor is duplicated instantly by a similar movement of the rotor of the motor. The generator rotor is mechanically connected to the water-level float, and the motor rotor mechanically to the indicating device in the power-house. The stator and rotor windings of the generator and the motor are electrically connected, and both machines can be located at practically any distance apart, wherever it is most desirable to place them. When the switchboard attendant wishes to send a signal he turns the handle connected to the Selsyn generator to the proper position on the dial. The movement of the generator behind the dial causes the Selsyn motor and the pointer on the indicator of the signalling pedestal in the generator room to take the same position. He then pushes a button to the right of the handle, which lights a lamp on the generator pedestal and rings a bell to attract the attention

of the machine operator. This operator then repeats this performance from the generator floor, and by pushing a button on the generator pedestal he lights a lamp and rings a bell on the switchboard, indicating that the signal was received and correctly interpreted. The switchboard operator then pushes another button, extinguishing the lamp and stopping the call bell, after which both operators move the respective handles to the "off" position. A complete description of this system will be found in *General Electric Review*, for March, 1921.

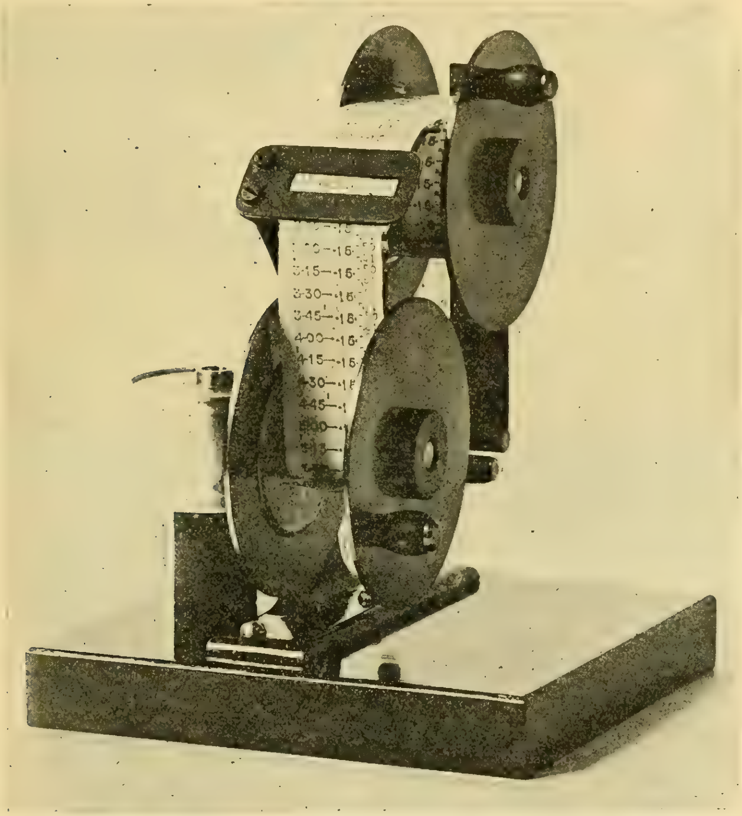


Fig. 156.—Tape Reel for Use with Water Stage Printing Register.

In installing an automatic register (Fig. 158) it is necessary to provide a well for the float, connected with the river by an intake pipe, a house to shelter the register, and staff or hook gauges with bench marks for checking the record and maintaining the datum. The well and the house should be located far enough back from the river to be out of

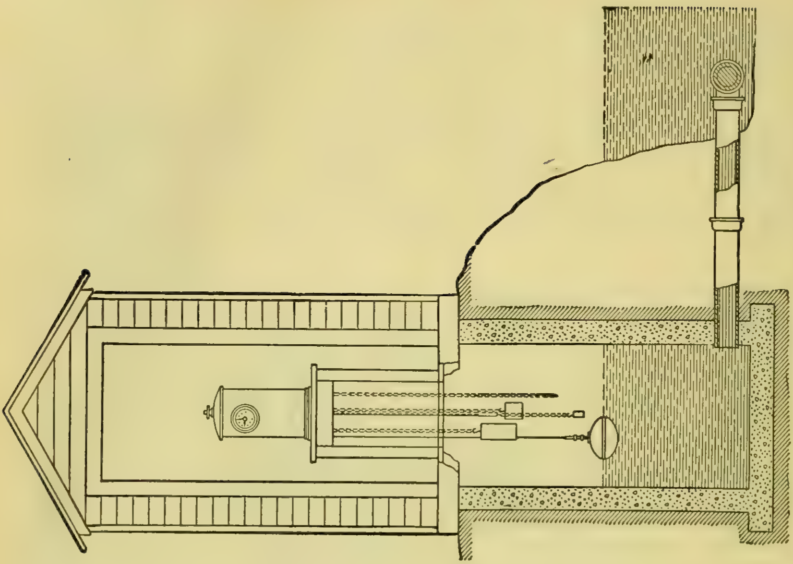


FIG. 158.—Method of Installing Automatic Water Stage Register.

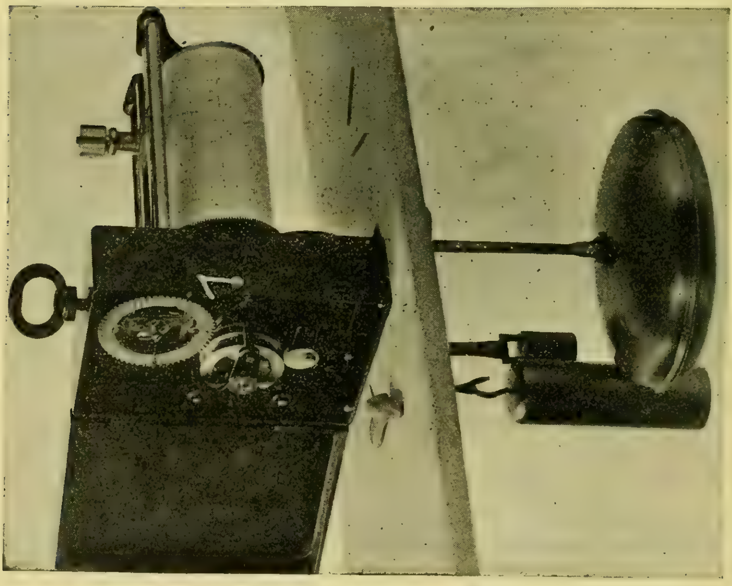


FIG. 157.—Automatic Graphic Recording Water Stage Register.
(Manufactured by W. & L. E. Gurley, Troy, N. Y.)

danger from floating ice or drift and to provide sufficient protection for the well and pipes to prevent their freezing. A permanent ladder should extend to the bottom of the well, so that the float and intake can be readily inspected. If the register is to be maintained for a long period, the well should be lined with concrete; otherwise a heavy plank lining may be used. The intake pipe should be placed well below the lowest stage of the river and provided with a screen for keeping out silt and foreign material. It should also be provided with check gate as it enters the well, so that the flow can be reduced if necessary, to eliminate wave action.

CHAPTER VIII

ELECTRICAL EQUIPMENT

1. GENERAL CONSIDERATIONS

THE principal engineering problems involved in the work of hydro-electric power stations have to do with what might be called application engineering. The various parts must be made to function as a whole, harmoniously and without interruption, the specific object in view being to supply power to the customer in the best manner and at the lowest cost. This involves an intimate knowledge of the characteristics of the hydraulic and the electrical apparatus, and of all the functions which the apparatus is expected to perform and the conditions to which it will be subjected in use.

Electrical Apparatus Involved. In hydro-electric power stations, the electrical apparatus involved consists of generators, exciters, transformers, circuit breakers and switchboards, reactors, lightning arresters, signal systems, relays, line entrances, transmission lines with their towers, insulators, and conductors. All electrical apparatus is subject to the limitation of heating, to electrical and mechanical stresses and much insulation is subject to a continual, if only very slight, deterioration.

In hydro-electric generators we must consider the following factors:

RATING
- Relative capacity of generator and water wheel

TYPE
- Vertical or horizontal

VERTICAL GENERATORS
- Bearings
  - Thrust
    - Types
  - Guide
    - Advantages of middle bearings
    - Disadvantages of middle bearings
    - Advantages of no middle bearings
    - Disadvantages of no middle bearings

- Lubrication
  - Central oiling system
  - Individual system
  - Small units
  - Lubrication of water-wheel guide
  - Water cooling
  - Filters
  - Oil
  - Pipes and fittings
- Hydraulic thrust
- Direction of rotation
- Over speed
- Shaft
  - One piece
  - Two piece
  - Hollow
- Coupling
  - Tapered bolts
- Collector rings
  - Located above generator
  - Located below generator
- Armature frame
- Thrust
- Foundation
  - Ring
  - Plates
- Transportation
  - Split frames
  - Special skids
- Assembly and erection
  - Assembly in factory
  - Assembly in field
  - Special wrenches
  - Lifting device
- Brakes
  - Type
  - Support
- Ventilation
  - Large stations
    - High and medium-speed machines
    - Slow-speed generators
    - Air washers
  - Small stations
- Galleries
- Stairways
- Screens
- Flywheel effect
- Voltage
- Windings and generator protection
  - Connections
  - Relays

    - Grounding
    - Fire protection
- Excitation
    - Direct-connected exciters
    - Auxiliary A.C. generators
    - Water-wheel driven
    - Motor driven (flywheel)
    - Voltage regulation
    - Type of regulator
    - Individual regulators
    - Common exciter bus
    - Complicated systems
- Rheostats
    - Exciter field rheostat
    - Generator field rheostat
        - Electrically operated
        - Hand-operated
        - When omitted
- Power station auxiliaries
    - Source of power for driving auxiliaries
- Tests
    - Factory tests
    - Field tests
    - Over speed
- Location of accessories

HORIZONTAL GENERATORS

- Bearings and lubrication
    - Weight to be supported
    - End thrust
    - Impulse wheels
    - Oiling system
- Direction of rotation (See Vertical Generators)
- Over speed (" " ")
- Shaft
- Transportation (" " ")
- Assembly and erection
    - Movement of stator
- Foundations
    - Buses and caps
    - Bolts
- Ventilation
    - Enclosed machines
- Flywheel effect
- Voltage (See Vertical Generators)
- Windings (" " ")
- Excitation (" " ")
- Voltage regulation (" " ")
- Rheostats (" " ")
- Auxiliaries (" " ")
- Tests (" " ")

In the choice of power transformers the following elements should be carefully considered:

Choice of transformers or auto-transformers
Type of transformer
  (*a*) Single-phase or three-phase
  (*b*) Outdoor or indoor
  (*c*) Methods of cooling
Voltage, taps, ratio, etc.
  (*a*) Step-up transformers
  (*b*) Step-down transformers
  (*c*) Transformers for specific devices
Reactance
Parallel operation
Connections
Accessories
  (*a*) Trucks
  (*b*) Thermometers and temperature indicators
  (*c*) Breathers and heaters
  (*d*) Bushings
  (*e*) Conservators
  (*f*) Oil
  (*g*) Standard and special accessories
Transportation and installation
Tests

In the application of oil circuit breakers the following points demand attention:

Normal current-carrying capacity
Voltage of system
Rupturing capacity
  This involves a study of the possible short circuits on the system, the setting of relays and speed of the switch
Automatic or non-automatic
  If automatic, operated by A.C. trip or D.C. trip and types of relays
Remote-controlled or manually operated
  If manually-operated, any special requirements in regard to levers, pipe mechanism, etc., should be mentioned
Equipped with bushing type current transformers or not so equipped
  Such current transformers should be used for relay action only, with possibly the addition of an ammeter. They are not accurate enough for metering
Outdoor or indoor
Type of mounting—in cells or on pipe framework
Kind of oil—ordinary or low temperature
Auxiliary devices
  Auxiliary switches for electrical interlocking or for controlling on auxiliary circuit
  Control switches
  Bell alarm relays
  Magnetic locks and interlocks
  Tank lifter

In all other apparatus the same general features should be considered as to limitation involved in the characteristics of the apparatus and in its relation to other apparatus with which it operates in coordination and also to the power house and installation in which it is located.

Before entering into a detailed study of the apparatus comprising the electrical equipment, there are two broad problems which require a careful consideration and must first be decided on, inasmuch as they have an important bearing on the entire equipment. These problems deal with the voltage and the frequency.

Voltage. There are three voltages between which a distinction must be made in a hydro-electric power system; viz., the generator voltage, the transmission voltage and the distribution voltage.

Generator Voltage. When additions to an existing plant or system are made, the voltage of the new generators is generally determined by that of the old machines, or by some other condition of the installation. In new installations, however, the generator voltage can be determined only after considering a number of factors. For example, a compromise must, as a rule, be found between the increased cost of a high-voltage machine and its control equipment as compared with the reduced cost of the busbars and connections caused by the smaller amount of copper required. Whether generators are to be wound for a high voltage for direct transmission, or for low voltage and step-up transformers, is to a certain extent also decided by the relative cost of the two methods. If economically feasible, the latter method with step-up transformers is the most reliable and to be recommended. In other instances the nature of a local load may be such that, by installing high-voltage generators, power for this load may be directly transmitted at the generator voltage; while at the same time step-up transformers may be provided for raising the pressure of the current which is to be transmitted for greater distances. The standard generator voltages are given under " Synchronous Generators."

Transmission Voltage. The transmission voltage should be chosen to insure the most economical ensemble. Many factors affect the problem variously, and their nature makes a mathematical expression difficult and, as a rule, unsatisfactory. The distance of the transmission and the load are naturally the factors which govern the choice of the voltage to the greatest extent. The cross-section area and, consequently, the weight to the transmission conductors, varies inversely as the square of the voltage for a given load. The cost of the conductors is, therefore, reduced 75 per cent every time the voltage is doubled, and it would consequently seem proper to use the highest voltage possible

in any given case. Though with increasing voltage, the cost of the conductors decreases, the cost of other apparatus and appliances increases. This involves transformers, switching equipment, lightning arresters and line structure and insulators, while, of course, the necessary safety requirements become stricter with higher voltages.

With very high voltages and long lines, the capacity current of the lines becomes considerable, especially in 60-cycle systems, and may reach values higher than the full-load current. Its greatest objection is that it loads the generators with current which represents no power, and where small units are used it may often render it impossible to throw one machine on the line alone. Much more serious, however, is the impairment of the voltage regulation incident to very long lines, i.e., the voltage variation between no load and full load, especially for inductive loads. By providing synchronous condensers, it is, however, possible to compensate for the wattless currents and improve the regulation.

Another factor which has a limited bearing on high potentials for transmission purposes is corona, as experience has shown that if the voltage on a given line is raised beyond a certain point the air at the surface of the conductors breaks down as an insulating medium and becomes luminous. The most serious objection to corona comes from the losses, which increase at a high rate as the voltage is raised above this luminous or so-called visual critical point. This critical voltage increases with the size of the conductors and their spacing, and by properly choosing these values the losses may be materially reduced or entirely eliminated. For high altitudes corona starts at lower voltages and this should be given careful consideration (see section on "Station Wiring").

The factors determining the proper transmission voltage are, as a rule, of an economic nature, and, while no fixed formula for determining the voltage can be given, in general it may be said that the most economical voltage is the one for which the annual cost of the energy loss added to the annual cost for depreciation and interest on the first cost, becomes a minimum. In determining the value of the energy loss, a mean value for a number of years should evidently be taken, and the value should be based on the cost for which the power can be produced. The interest and depreciation, as well as operating charges, should only be applied to the items that will vary with changes in the voltage, such as the line conductors and tower line, the generating and substation buildings, transformers, switching equipment and lightning arresters.

An approximate average scale of voltages, for transmission lines

up to 250 miles in length, is given in Fig. 159. With large loads, however, these voltages may have to be exceeded.

Distribution Voltage. The selection of the proper distributing voltage is also an important matter. Where large territories have to be served from high voltage transmission circuits, the general practice seems to indicate that the most economical voltages for such systems are in the neighborhood of from 22,000 to 44,000 volts. A second or

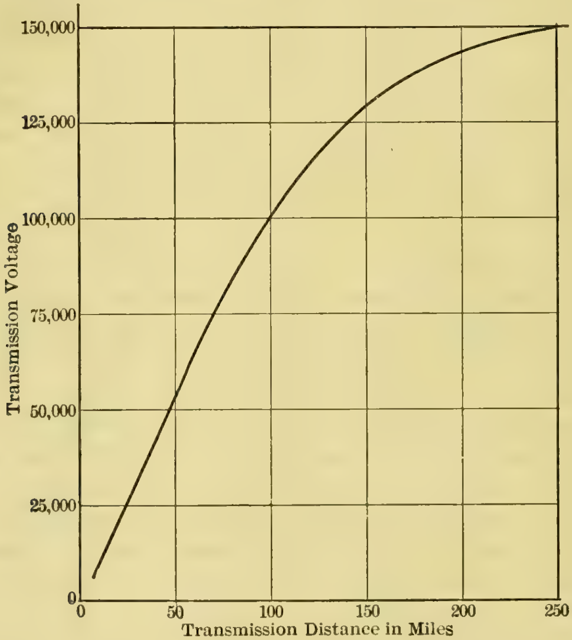


FIG. 159.—Approximate Voltages for Power Transmission of Various Lengths.

even third transformation is, therefore, necessary before the power can be used for motors or lighting.

The distribution of alternating current for general commercial purposes is accomplished almost universally by 2300-volt mains, supplying step-down transformers located near groups of consumers, whose premises are served by secondary mains at 115 to 230 volts. Single-phase circuits are quite generally used for lighting service, while power service is, as a rule, given from two-phase or three-phase mains. The former system is used chiefly where this method of distribution was established in the early period of the development, and where it is too

extensive to warrant a change to the three-phase system, which is standard for all new installations where a polyphase supply is wanted for power service.

For small- and medium-sized cities, a three-wire, "delta" connected, 2300-volt system is very generally used for power distribution, while for larger cities there is a steady trend toward the four-wire, "Y"-connected system operating at 2300–4000 volts. There are numerous advantages with this system where feeders are extended more than 2 miles from the point of supply, and where adjacent towns within a radius of 5 miles may be served without step-up transformers or substations. It is possible to regulate the phases separately, and there is not so much of a necessity for maintaining a carefully balanced load. Even for secondary distribution, the four-wire, three-phase system, operating at approximately 115–200 volts, is being generally used. With this system, lighting and motor service may be given for all ordinary retail purposes from the same circuit, the principal disadvantages being that there are three phases to be kept balanced.

Frequency. There are now two frequencies recognized in this country as standard, namely, 25 and 60 cycles. The former, primarily because of the limitations it imposes in the selection of motor speeds, and its inferiority for lighting, is fast being superseded by the latter. In fact, at present, 60 cycles is now almost universally adopted throughout the country. While we are adopting 60 cycles, Europe has come to regard 50 cycles as most desirable, and has adopted it as a standard frequency.

In the following discussion, the influence of frequency will be treated in connection with frequency changers, generators, transformers, transmission lines, induction motors, synchronous converters, railroad work and illumination.

Frequency Changers. Frequency changers are primarily used for effecting a change in frequency. They are either utilized for obtaining a frequency high enough for lighting purposes from a low-frequency system, or, as a means of interchanging power between systems operating at different frequencies.

The change from 25 to 60 cycles or vice versa requires a set running at 300 R.P.M., which is a serious limitation because this speed is much too low for the economical design of frequency changers of small or moderate size. If an exact ratio is not absolutely necessary, as when power is taken from an existing system for lighting and industrial purposes, and the frequency changer is not intended for tying two generating systems together, the available range of speed is greatly

increased, as shown in the following table. The first and third combinations are mostly used.

TABLE XL

FREQUENCY-CHANGER COMBINATIONS

Frequency.		Poles.		Speed.	Generator Frequency.
Motor.	Generator.	Motor.	Generator.		
25	62.5	4	10	750	4.17 per cent high
25	62.5	8	20	375	4.17 per cent high
25	60	10	24	300	Exact
25	58.3	6	14	500	2.78 per cent low
25	56.3	8	18	375	6.18 per cent low
60	26.7	18	8	400	6.8 per cent high
60	25.7	14	6	514	2.8 per cent high
60	25	24	10	300	Exact
60	24	20	8	360	4 per cent low
60	24	10	4	720	4 per cent low

While synchronous motors are almost invariably used with frequency changers, induction motors may be used if proper arrangements are provided for adjusting the slip so as to insure a satisfactory parallel operation. This adjustment, of course, means the introduction of a permanent resistance and a corresponding loss, and is, therefore, undesirable unless other advantages of greater importance can be obtained. Where only one set is required, speed adjustment is not necessary, and the motor may be designed with a slip which will just be sufficient to bring the generator frequency to the right value.

Generators. The frequency of synchronous generators in alternations per minute is equal to the number of poles times the revolutions per minute, and the periodicity or cycles per second is shown by the following equation:

$$\text{Cycles} = \frac{\text{Number of poles} \times \text{revolutions per minute}}{120}.$$

Owing to the fact that there is a natural relation between the windings of electrical apparatus, which varies inversely as the square of the frequency, the higher the frequency the greater is, in general, the peripheral velocity at the same revolutions per minute. Increase in peripheral velocity means a larger diameter with a smaller length and a better natural ventilation. The higher periodicity in definite pole machines is also preferable in that the load of the rim of the spider is

better distributed and smaller in amount at the point of attachment of poles. The induced E.M.F. is directly proportional to the frequency, and for modern designs there is hardly any difference in efficiency. The cost is somewhat increased by a decrease in frequency, there being a natural tendency for 25-cycle apparatus to be heavier than 60-cycle.

Transformers. The frequency has a very important bearing both on the design and operation of transformers. With transformers and other electric apparatus using two windings and an iron core, the ratio of turns, other factors remaining the same, will vary approximately inversely as the square root of the frequency. The lower the frequency the larger the flux, and the larger the number of turns for the same voltage. Therefore, transformers increase in cost and weight as the frequency decreases.

The regulation of 25-cycle transformers is not quite as good as for 60-cycle, on account of the increased drop, due to the great number of turns and their increased mean length; and the efficiency is also slightly less.

Operating 25-cycle transformers on a 60-cycle circuit decreases the flux density and the core loss. Operating a 60-cycle transformer on a 25-cycle circuit increases the density and core loss, and, in general, gives a prohibitive exciting current. Frequency also enters into the mechanical forces to which a transformer may be subjected, as the reactance increases with the frequency, and, while the mechanical force varies directly as the square of the current, a 25-cycle transformer operating on a 60-cycle circuit would be subject to about one-half the mechanical strains on short-circuit. The reactance of power transformers generally ranges from 6 to 10 per cent.

Transmission Lines. Transmission lines are designed from considerations of regulation and efficiency and, as explained more fully under "Voltage," the regulation is better as the frequency is lower. Twenty-five cycles would therefore be preferable to 60 cycles, considering the line regulation alone. As stated above, the capacity current also plays an important part with small units and high voltages, often rendering it impossible to throw one machine on the line alone. Both the reactance and the capacity current of the line are proportionate to the frequency, as shown by the following equations:

$$\text{Reactance} = 2\pi f L;$$

$$\text{Capacity current} = 2\pi f C E.$$

The resistance of wires and cables carrying alternating currents is also affected by the frequency, in that the current is not distributed

uniformly over the cross-section of the conductors, the current density being higher near the periphery. This is known as "skin effect" and results in an increased effective resistance. The effect is, however, negligible for low frequencies and small conductors, but increases rapidly for higher frequencies and large conductors. With magnetic material it is much higher than with non-magnetic, and its effect should be considered where iron conductors are used and for heavy copper work.

Induction Motors. The speeds of 25-cycle induction motors for general application are practically limited to 1500, 750, 500 and 375 R.P.M., while the corresponding speeds for 60-cycle motors would be 1800, 1200, 900, 720, 600, 514, 450, and 400 revolutions.

The efficiency depends upon a number of features. The lower frequency will, of course, tend to make the iron loss less, but, on the other hand, the copper loss will be considerably greater on account of the longer end connections, and, as a rule, the efficiency is found to be somewhat lower for low- than for high-frequency motors.

The power factor of an induction motor is expressed by the ratio $\frac{\text{kw. input}}{\text{kv.a. input}}$. It is affected by the reactance and the magnetizing current. At constant line voltage the latter remains practically constant, while the former varies with the current. The shape of the power-factor curve, that is, the power factor at fractional loads and overloads, therefore, depends upon the relative values of the magnetizing current and the reactance.

$$\text{Power factor} = \cos \phi = \frac{R}{Z}.$$

A motor with a relatively large magnetizing current and a low reactance will, in general, have a low power factor at fractional loads and a rapidly increasing power factor at higher loads, while a motor with a relatively low magnetizing current and a high reactance will have a high power factor at fractional loads and only a slightly greater power factor at overloads.

The 25-cycle motor has an inherently lower reactance and requires less magnetizing current for a given speed, for which reason its power factor is higher than for high-frequency motors.

The starting torque and the maximum torque depend inversely on a function of the reactance, and are, therefore, higher for low frequencies.

The starting torque of an induction motor is equal to:

$$k \frac{E^2 r_1}{Z^2};$$

the starting current is equal to

$$\frac{E}{Z};$$

the running torque is equal to

$$k\frac{E^2sr_1}{[(r_1+sr)^2+s^2X^2]};$$

the maximum torque is equal to

$$k\frac{E^2}{[(2(r+\sqrt{r^2+X^2})]},$$

where k = constant;
E = applied voltage;
s = slip;
r = stator resistance per phase;
r_1 = rotor resistance per phase;
X = total reactance;
Z = total impedence.

Comparing the weights, based on motors of the same capacity and speed, it is found that, on the average, 25-cycle motors will weigh about 15 per cent more than 60-cycle motors. For the smaller sizes there is very little difference in the cost, but as the sizes increase there is a marked difference in favor of the 60-cycle motors.

Synchronous Converters. A synchronous converter being in effect a combination in one machine of a synchronous motor and a direct current generator, the important factors in which the frequency is concerned have to do almost entirely with the continuous-current side. The continuous-current generator, as a rule, runs at frequencies much below 25 cycles, and at the frequencies of synchronous converters, especially for 60 cycles and above, the problems of commutation and commutator construction become of importance. The pole pitch on the commutator, armature or field, is the space passed through in one alternation, and it is thus seen that there is a natural tendency for higher peripheral speeds at the higher frequencies, and it is the limitation of peripheral speed which fixes the limits of design.

Improvements in design have made the 60-cycle synchronous converter entirely satisfactory for the conditions under which such machines operate. The efficiencies of the two types are practically the same.

Railroad Work. Twenty-five cycles has heretofore been recognized as the standard frequency for railway systems in this country. Until a short time ago, all systems were of the alternating-current-direct-current type, alternating current being generated and transmitted to the

various substations, where it was changed to direct current by means of synchronous converters. The choice of this frequency was, therefore, chiefly caused by the less satisfactory operation of the earlier types of 60-cycle converters, but these machines are now giving entirely satisfactory service and are in very general use.

With the introduction of the alternating current railway motor, 60 cycles is entirely eliminated, the frequency in use for this service being 25, $16\frac{2}{3}$ and 15.

Illumination. Where alternating current is used for lighting, the 60-cycle frequency is generally used. No arc lamp has as yet been developed that will operate with entire satisfaction on frequencies of less than 40 cycles, and incandescent lamps cannot be used to advantage on frequencies of less than 30 cycles. Low-voltage incandescent lamps show no flicker; but the effect of fatiguing the eye is noticeable at 25 cycles, especially in high-voltage lamps.

2. SYNCHRONOUS GENERATORS

Alternating-current generators may be classified into two general classes according to their general characteristics: Synchronous generators and Induction generators. The former type is used almost exclusively, the latter being used only occasionally for special cases, as explained under the section on Induction Generators.

The generator forms one of the most important parts of the equipment in a hydro-electric development, and a thorough knowledge of its characteristics and design is of the utmost importance. The subject will, therefore, be treated somewhat more in detail than would at first seem desirable.

General Description. Most alternating-current generators are of the revolving field type. The armature, which is then stationary, consists of a laminated iron core supported by a cast-iron frame, the inside periphery of the core being slotted to carry the armature winding. Inside the stator revolves the rotor or revolving field system, and as synchronous generators are not self-exciting, the field excitation is obtained from some external direct-current source.

Induced E.M.F. The E.M.F's. and currents are alternating, i.e., have one-half wave or alternation, first positive and then negative, for each pole passed by a given armature conductor. A cycle is a complete wave of two alternations, and the frequency is equal to the product of the number of pairs of poles and the speed of the machine in revolutions per second; it is, therefore, strictly proportional to the speed of the machine.

The wave shape of the E.M.F. depends on the distribution of the magnetic flux at the armature surface, the distribution of the armature coils and the coil pitch; and the total E.M.F. is the sum of the E.M.F. waves in the different armature conductors, added in the proper phase relation. The instantaneous values of the E.M.F. and current

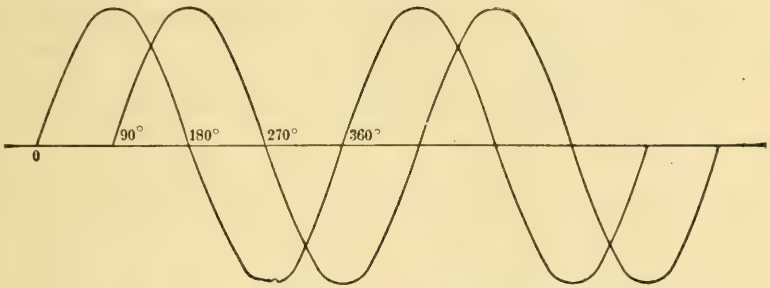


Fig. 160.—Two-phase Alternating Current.

are constantly changing from maximum positive to maximum negative, and the specified or effective value is equal to the square root of the average value of the square of the instantaneous values. For a true sine wave shape it is equal to the maximum value divided by $\sqrt{2}$.

The phase relation differ symmetrically for polyphase systems. In the two-phase system the terminal voltages of the two circuits differ

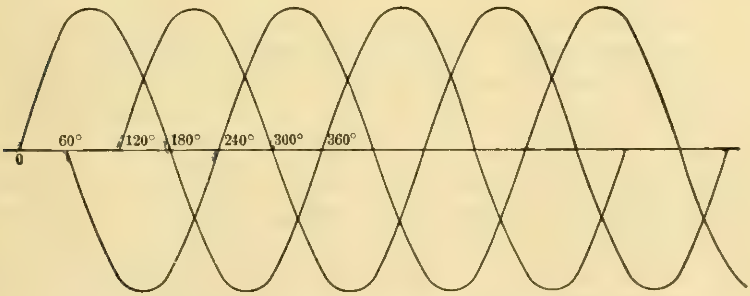


Fig. 161.—Three-phase Alternating Current.

in phase by 90 electrical degrees, Fig. 160, and in the three-phase system, the terminal voltages of the three circuits differ in phase by 120 electrical degrees, Fig. 161. The terminal voltage of two-phase generators is equal to the E.M.F. of the armature circuits, and the line current is equal to the current in these circuits. For three-phase machines, however, the armature winding can be connected either Y or Δ, which will be discussed more fully later. If the winding is Y-connected, then

the terminal voltage is equal to $\sqrt{3}$ times the E.M.F. per armature circuit, and the line current equal to the armature current. If the winding is Δ-connected, then the terminal voltage is equal to the E.M.F. per circuit and the line current equal to $\sqrt{3}$ times the current in the armature circuit. In general, in speaking of current and voltage in a three-phase system, " current " is understood to mean the Y-current or current per line, and " voltage " the Δ-voltage or voltage between line wires. This subject is covered more fully in the section on " Armature Connections."

The E.M.F. induced in the armature circuit is determined by the following formula:

$$E_g = 2 \times k_f \times k_d \times k_p \times f \times n \times \phi \times 10^{-8};$$

in which k_f = wave form factor;
k_d = distribution factor;
k_p = winding pitch factor;
f = frequency in cycles per second;
n = number of armature conductors connected in series per phase (twice the number of turns per phase);
ϕ = flux per pole in maxwells.

The form factor of an E.M.F. wave is defined as the ratio $= \frac{\text{effective voltage}}{\text{average voltage}}$, and for a sine wave this value is equal to 1.11.

The armature winding is generally distributed; that is, the armature conductors are placed in more than one slot per pole per phase. The principal advantage of such a distribution is the closer approximation toward a sinusoidal wave form, while, on the other hand, the total radiating surface of the coils is increased.

With a distributed winding, the E.M.F. will, however, be somewhat reduced, because the voltage induced in the conductors in the different slots are somewhat out of phase with one another, and for this reason the distribution factor k_d, for which the values are given in Table XLI, must be introduced in the formula. With two-layer windings the value of k_d should correspond to the number of slots per pole per phase.

The windings may be arranged for full or fractional pitch. In the former case the coil spans a distance exactly equal to pole pitch while in the latter case it spans a lesser distance. Fractional pitch windings are very generally used, the advantages being a better wave and shorter end connections of the windings, resulting in a saving of armature copper, besides making the machine shorter. This is especially the case for machines with a small number of poles. It is evident

TABLE XLI

VALUES OF DISTRIBUTION FACTOR k_d

Slots per Pole per Phase.	Two-phase.	Three-phase.
1	1.000	1.000
2	0.924	0.966
3	0.911	0.960
4	0.907	0.958
5	0.904	0.957
6	0.903	0.956

that the E.M.F's. induced on both sides of the same coil are not exactly in phase with each other in a fractional pitch winding, so that a larger flux will be required than with a full-pitch winding. This is allowed for in the voltage formula by introducing a winding pitch factor, k_p, its values for different per cent pitch being given in Fig. 162. They are simply based on the formula:

$$k_p = \sin\left(\frac{x}{100} \times 90°\right),$$

where x is the per cent pitch.

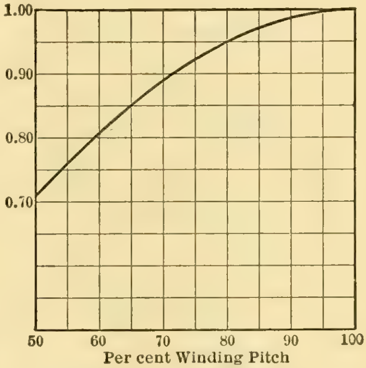


FIG. 162.—Values of Winding-pitch Factor.

For single-phase generators the armature is generally wound like that of a three-phase machine, one phase being normally left idle. With this arrangement the distribution factors k_d are the same as given for three-phase windings. If the winding is furthermore distributed as with purely single-phase generators, when it covers considerably more than two-thirds of the armature surface, the values of these distribution factors should be reduced.

The flux ϕ, obtained from the previous formula is that which is necessary in the armature for inducing the required E.M.F., i.e., the useful flux. Owing to the leakage between the poles it is, however, necessary to provide a greater flux in the field poles and the yoke to compensate for this leakage, and this must be considered when calculating the ampere turns of the field winding. This increased flux is obtained by multiplying the useful flux by a leakage coefficient. The average values for this factor at no load, depending on the diameter per pole, may be obtained from Table XLII.

TABLE XLII

POLE LEAKAGE COEFFICIENTS

Diameter per pole, inches......	2	3	4	5	6	7	8
Leakage coefficients............	1.4	1.35	1.3	1.26	1.22	1.18	1.16

Effect of Power Factor on Operation. Assuming all conditions except the load constant, the terminal voltage of an alternating-current generator will fall as the load increases. This is due to the resistance of the armature conductors and the synchronous reactance, the latter combining the effects of the armature reaction and the armature reactance or self-induction. For a constant terminal voltage with increased load, the armature resistance and self-induction require an increase in voltage, while the demagnetizing effect requires only an increase in the magnetic flux to make up for the reduction in flux caused by the armature current. The latter does not require any increase in the generated voltage since the action is confined to the magnetic flux.

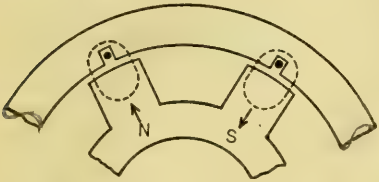


FIG. 163.—Armature Reaction. Current in Phase.

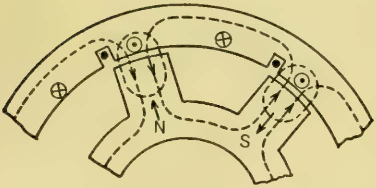


FIG. 164.—Armature Reaction. Current Lagging.

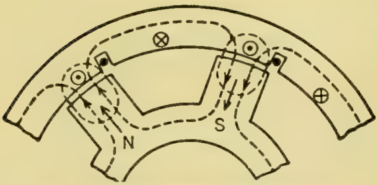


FIG. 165.—Armature Reaction. Current Leading.

• Armature Conductor
⊙ In-phase Component of Armature Current
⊕ Wattless Component of Armature Current

The drop in voltage, due to the armature resistance, requires no explanation beyond the statement that the voltage drop is in phase with the current flowing.

The armature reaction, which represents the resultant E.M.F. of the armature currents, depends on the current and the number of effective turns in series per pole per phase. It may have a magnetizing or demagnetizing effect, or it may shift the field flux from one side of the pole to the other, or its effect may be a combination of the two. The energy component of the current will only cause a shifting or distorting effect, while the wattless component will cause a demagnetizing or magnetizing effect, depending on whether the current is lagging or leading. These effects are illustrated in Figs. 163 to 165.

Figure 163 represents two conductors of an armature coil. These are midway under a north and south pole, respectively, and the E.M.F. induced in the coil is obviously a maximum for this position. The current in the coil will also have the maximum value as it is in phase with the E.M.F., and the flux produced by the same will have a cross-magnetizing effect not directly opposing the field ampere-turns, but simply causing a distortion of the field flux. The current in the armature, however, always lags behind the induced E.M.F. by reason of the inductance, and even with unity power factor in the external circuit, the armature reaction is demagnetizing to a certain extent.

In the position shown in Fig. 164 the E.M.F. generated in the coil has a value somewhere between zero and maximum, zero corresponding to a coil position midway between the field poles. The armature current, which, in this case, is lagging somewhere between 0° and 90°, can be considered as made up of two components, an in-phase component having a cross-magnetizing effect, and a 90° lagging component having a demagnetizing effect. At zero power factor the wattless armature current, lagging 90°, has a maximum value, and consequently the greatest demagnetizing effect.

In Fig. 165 the current is leading and its effect is just opposite to that produced when the current was lagging. It is thus seen that, in a generator, the field is weakened by a lagging current and strengthened by a leading current.

The armature reaction in polyphase generators is materially different from that in single-phase machines. In the former its total effect combines that of the several phases and has a constant value, provided the load is balanced. If unbalanced it will be of a more or less pulsating nature of double frequency, as is always the case in single-phase generators.

The armature self-induction is caused by the leakage flux which is set up by the armature current and which does not interlink with the field flux. Since the armature current is alternating, the local or leakage flux, which does not become linked with the main field, will be continually altering in magnitude and direction, so that there is set up a self-induced E.M.F. proportional to the leakage flux of each phase and lagging 90° behind the current. The armature leakage is usually local, and thus a distributed winding with many slots will have a smaller leakage inductance, since the flux generated by each unit of current will be linked with a smaller number of ampere turns.

The exact value of the self-induction of an armature winding is somewhat difficult to determine, its magnitude depending upon the reluctance of the paths taken by the leakage flux. There are, however,

several methods in use which give results which agree very closely with those afterwards obtained experimentally.

If L is the self-induction, expressed in henrys, and f the frequency,

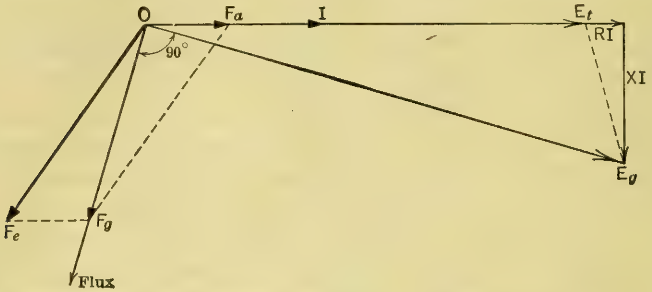


FIG. 166.—E.M.F. and M.M.F. Diagram. Non-inductive Load.

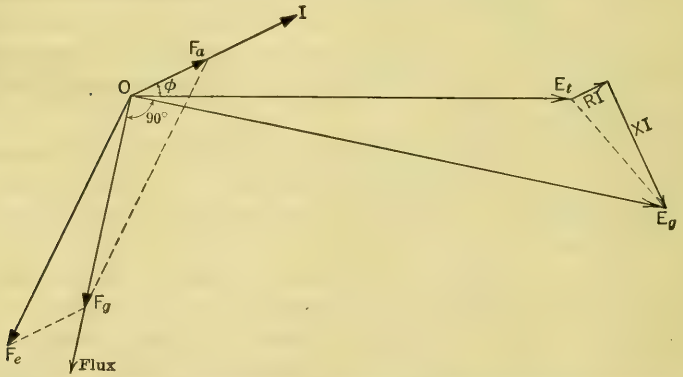


FIG. 167.—E.M.F. and M.M.F. Diagram. Lagging Inductive Load.

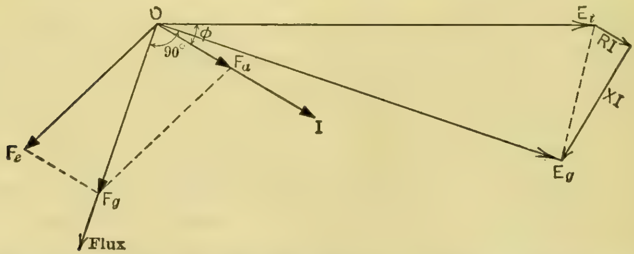


FIG. 168.—E.M.F. and M.M.F. Diagram. Leading Inductive Load.

the inductive reactance is equal to $2\pi fL$. It is of the same nature as resistance and is expressed in reactance ohms. The counter E.M.F. caused by it is lagging 90° behind the current, and the E.M.F. which it

consumes and which has to be impressed, must thus be leading 90° ahead of the current. This is illustrated in the diagram, Fig. 166, where the vector XI denotes the E.M.F. consumed by the reactance X.

The vector E_t represents the terminal E.M.F. and I the current, which in this case is in phase with the terminal E.M.F., the load being non-inductive. The E.M.F. consumed by the resistance is equal to RI, in phase with I, and E_g is the E.M.F. which must be induced to obtain a terminal E.M.F. E_t and overcome the effects of the resistance and reactance, thus causing a current to flow.

The flux required to produce E_g is 90° ahead of this E.M.F., the magneto-motive force or ampere-turns to produce the same being

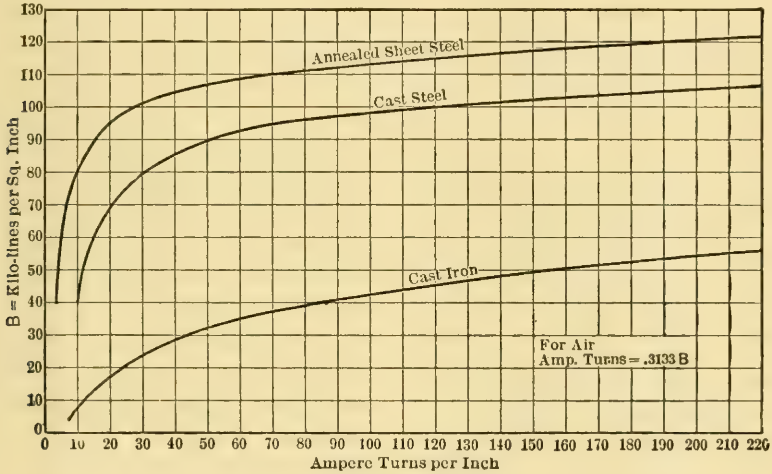


Fig. 169.—Saturation Curves.

represented by F_g. Owing to the demagnetizing effect of the armature current, i.e., the armature reaction, the vector F_g is the resultant of the M.M.F. of the armature current F_a, and the total impressed M.M.F. or field excitation F_e. The M.M.F. F_a is in phase with the current, and after the value of F_g and F_a has been determined, the necessary field excitation F_e is obtained by completing the parallelogram.

The effect of a lagging inductive load is shown in Fig. 167 and of a leading inductive load in Fig. 168. For the same terminal voltage E_t, it is seen that, as compared with a non-inductive load, a much higher field excitation is required with a lagging inductive load, and a lower field excitation with a leading inductive load. The field excitation required to produced the terminal voltage E_t at open-circuit would be obviously less than the field excitation with non-inductive load.

Field Excitation. The excitation or field ampere-turns required to produce the magnetic flux which is necessary in order to induce a desired E.M.F. depends on the character of the magnetic circuit, i.e., on its dimensions and on the material of which it is made up. The values are readily obtained by reference to standard saturation curves, similar to the ones shown in Fig. 169, these curves, of course, depending upon the qualities of the iron or steel which is used. The total magneto-motive force per magnetic circuit is equal to the sum of the M.M.F's. necessary for establishing the required flux in the separate parts of the circuit which are in series; viz., the pole pieces, the field spider, the air gaps, the teeth and the armature core.

The relation of the E.M.F. produced by an alternator at no-load, i.e., open circuit, to the field current when the alternator is driven at constant speed is represented by the no-load saturation curve. Such a curve is shown by curve *A*, Fig. 170, and it is seen that this curve is almost a straight line for small exciting currents. At low excitation, the reluctance of the air gap is very high and that of the iron very low, and, therefore, the former may be considered as constituting the entire reluctance of the magnetic circuit. Since the reluctance of air is constant, regardless of the flux density, at small excitations the flux will be proportional to the magneto-motive force, and, therefore, the open circuit voltage is proportional to the field current; hence, the curve is straight. As the field becomes stronger, however, the proportion of the air-gap reluctance to the entire reluctance decreases because the permeability of iron decreases with increased flux density, and, therefore, the E.M.F. increases less rapidly with increased excitation.

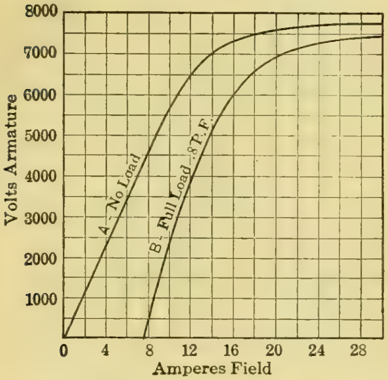


FIG. 170.—Alternator Characteristics.

It was pointed out in the previous section that when a current is flowing in the armature circuit, i.e., under load, the field ampere-turns required to maintain normal terminal voltage, exceed the no-load ampere-turns required for normal voltage, owing to the resistance and the synchronous reactance of the armature circuit. A number of more or less accurate methods have been proposed for calculating the above components, and thus determining the required field excitation at full load. Knowing the resistance and the leakage reactance or self-induc-

tion of the armature, the voltage drop caused by these is added vectorially to the terminal voltage, this giving the voltage which must be induced (see Figs. 166 to 168). Knowing from the no-load saturation curve the required net excitation at this voltage, and correcting it for the effect of the armature reaction, we obtain the necessary total field ampere-turns. The results of such calculations for different loads and power factors are represented by the load-characteristic curves. Such a full-load characteristic of an alternator is shown by curve *B*, Fig. 170.

In order to get the best combination for automatic voltage regulation an alternator should preferably have a range in excitation from

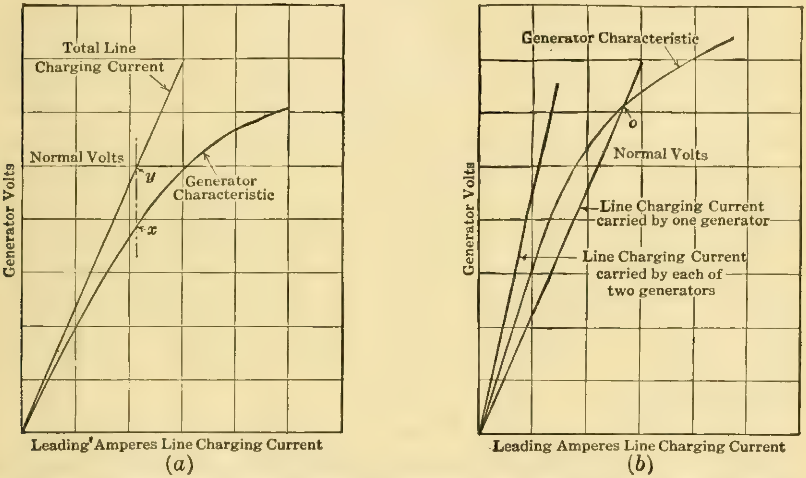


FIG. 171.—Volt-ampere Characteristics of Generator for Charging Long Transmission Lines.

no-load to maximum load, with approximately 80 per cent power factor, of the ratio of not more than 1 to $2\frac{1}{2}$. With 125 volts excitation, the voltage should, therefore, not be allowed to exceed 125 volts at maximum load, 80 per cent power factor, and the corresponding no-load excitation should be about 50 volts. Should the excitation voltage be 250, the same ratio should hold true. Generators supplying long transmission lines are in many instances required to work over a much greater range than 150 per cent because of the capacity effect of the line. This is also the case with synchronous condensers, which may have to operate from full capacity power-factor lagging to full capacity power-factor leading, thus requiring an excitation voltage of extreme limits.

When a generator is to be used for supplying power over long

transmission lines, the relation of its characteristics to those of the line becomes important and the two must be considered together. To insure stable operation, the saturation characteristic must lie below the line charging characteristic, as shown in Fig. 171a. This insures stable operation, because a given voltage will produce less line charging current than is required to excite the generator to that voltage. As explained on page 285, a leading current will cause an increase in the field strength, and the line charging current will therefore tend to magnetize the generator to a value corresponding to this, that is, to point X in diagram *a*. A certain field excitation is then necessary to bring the voltage from x to y, that is, up to normal value.

If, on the other hand, the saturation characteristic lies above the line charging current characteristic, as shown to the right in Fig. 171*b*, it is evident that a given voltage will produce more line charging current than necessary to excite the generator to that voltage, with the result that the generator will build up to a voltage corresponding to that current. This, in turn, will cause the line to be charged at a higher current, which will build up a higher voltage, etc., until the intersecting point o is reached. This building up will take place very rapidly, and the final voltage (at o) may be much higher than is safe either for the generator or the line. On the other hand the charging current corresponding to this voltage may be too much for the generator to carry. It is thus seen that this condition is unstable and should be avoided.

In a case like that last referred to, it might be possible to charge the line by two generators operated in parallel, in which case each machine would only carry one-half of the charging current, the condition being as shown by the left charging current characteristic in diagram *b*, and thus identical with the condition represented by diagram *a*. The generators should first be synchronized and excited with enough field to give about 15 per cent of normal voltage, which should be sufficient to keep the machines in synchronism.

The excitation required varies considerably for different machines, depending upon the size, the number of poles, the speed and the regulation. For alternators of different capacities, but otherwise similar, the relative excitation naturally decreases as the size of the alternator increases. High-speed machines generally require less excitation than slow speed, owing to the smaller number of poles. With a large number of poles, however, the air gap is usually smaller, and this will somewhat offset the higher excitation for slow-speed machines. In general, it may be said that small machines with many poles require a proportionally large excitation, and large machines with few poles a small

excitation. The curves given in Fig. 172 give the approximate excitation required by water-wheel-driven synchronous generators. The values given are per kv.a. per R.P.M. of the generator capacity, and are based on a maximum continuous rating at 80 per cent power factor.

Regulation. The regulation of an alternating-current generator is the rise in voltage when a specified load at specified power factor is reduced to zero, the speed and field excitation remaining constant. It is expressed in per cent of normal rated-load voltage, and unless otherwise specified is understood to refer to a non-inductive load.

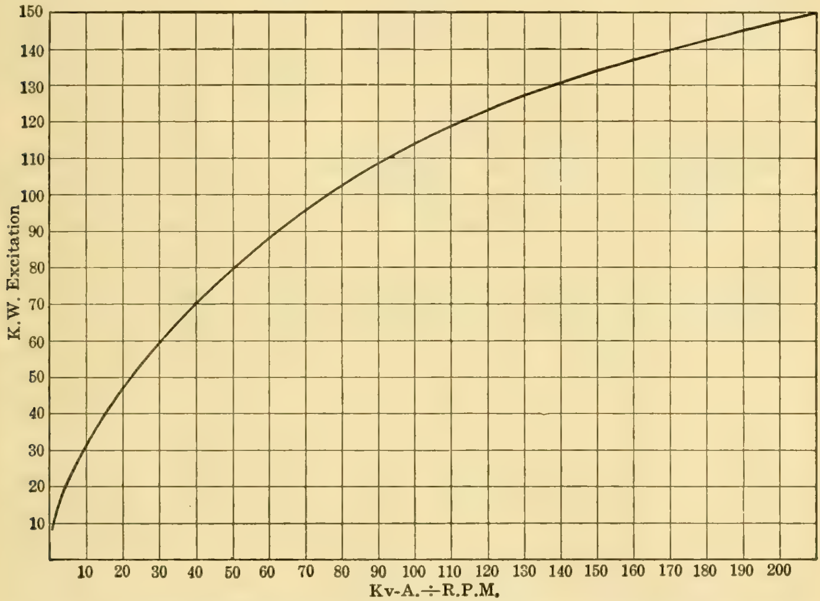


FIG. 172.—Approximate Excitation of Water-wheel-driven Three-phase, Sixty Cycle Generators. Per kv.a. per R.P.M. Based on Maximum Ratings at 80 per cent Power Factor.

A close inherent regulation was formerly considered one of the essential requirements of a good generator, but fortunately this idea is now entirely changed. A low percentage regulation may be obtained in two ways; first, by designing the generator with a field magnetically strong as compared with the armature, so that the self-induction and demagnetizing effect of the armature is comparatively small, resulting in a small increase in field current required to maintain normal voltage with increase in load; and, second, by saturating the magnetic circuit, particularly in the field, where high densities do not increase the losses or temperature rise. Both of these methods are, however, detrimental

to the present-day operating practice. A decrease in the synchronous reactance would proportionally increase the short-circuit currents of the machine and dangerously increase the severe mechanical strains produced by the same on the apparatus, as these increase with the square of the current. With these regulators a close inherent regulation machine is not necessary as a good regulation of the system can, nevertheless, be maintained. The regulator automatically increases the field excitation as the load increases and thus maintains a constant terminal voltage. If desired, it can also be adjusted so as to increase the voltage with the load and compensate for the line drop.

Modern water-wheel-driven alternators have a regulation at unity power factor of around 15 to 18 per cent. This is considered entirely satisfactory, as the voltage regulation is best taken care of by automatic voltage regulators.

Short-circuit Current. In speaking about the short-circuit current of an alternator, distinction must be made between the instantaneous short-circuit current and the sustained or permanent short-circuit current.

The sustained short-circuit current of an alternator is limited by the armature resistance and reactance, as well as its reaction on the field. It is equal to

$$I=\frac{E}{Z_s},$$

where E is the generated E.M.F. corresponding to the field excitation, and Z_s the "synchronous impedance," representing the combined effect of the above three factors. This formula, therefore, gives the value of the sustained short-circuit current, while its instantaneous value will be very much higher. This is due to the fact that in the first instant, when the generator is short-circuited, the current is limited only by the resistance and self-induction of the armature circuit, while a time lag of sometimes a few seconds takes place before the armature reaction becomes effective. The armature resistance and reactance are thus the only two quantities that limit the instantaneous short-circuiting current. This limiting effect is, however, not constant, but decreases slightly with high short-circuiting currents owing to their saturation of the magnetic field.

Figure 173 represents an oscillogram of a typical three-phase short circuit, the generator being short-circuited at the terminals of the armature winding. Comparing the currents for phases A and C, it is noticed that the latter gives an approximately symmetrical relation of the current crests with respect to the zero-axis, while in the former

case the wave is displaced so that the maximum peak of the initial current is nearly double that of phase A. This phenomenon is dependent upon the point of the potential wave at which the short circuit is established, and it is possible, by short-circuiting at different points on the normal potential wave, to obtain short-circuit current waves ranging anywhere from those symmetrical about the zero axis to those totally unsymmetrical.

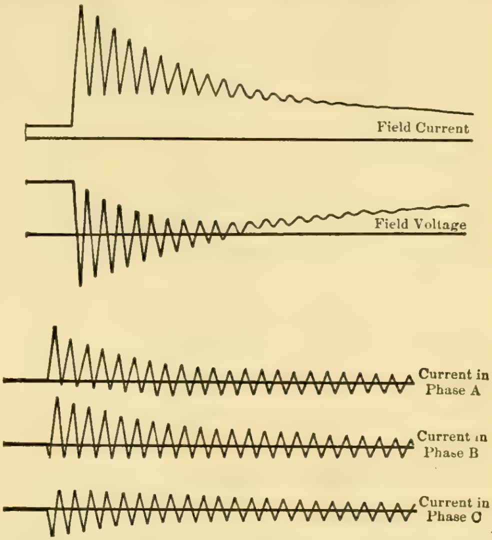


FIG. 173.—Oscillogram of Three-phase Alternator Short Circuit.

It is customary to speak of the value of generator reactance which limits the flow of current at the instant of short circuit as the transient reactance, which includes the self-induction of both field and armature circuits. This reactance is always associated with the effective or root-mean-square value of a symmetrical alternating current wave.

Referring to Fig. 174 showing the short-circuit current of a genera-

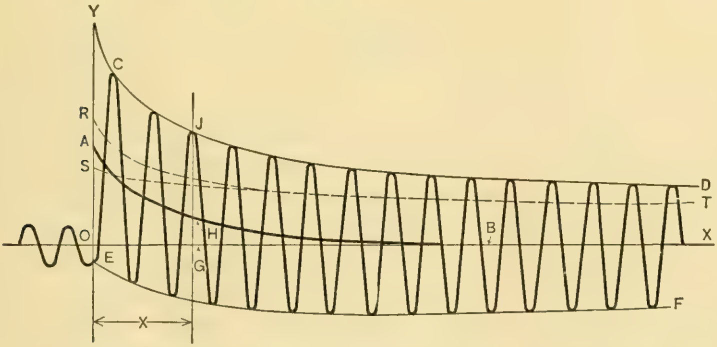


FIG. 174.—General Characteristics, Illustrating Behavior of Generator Current when Short-circuited from Full Load at 0.8 Power-Factor.

tor based on an unsymmetrical wave, CD is a curve drawn through the maxima of the wave of the total current; EF, a curve drawn through the minima, and AB is a curve drawn midway between CD and EF,

cutting everywhere the vertical between CD and EF. The wave of total current whose crests lie along the curves CD and EF and whose ordinates (magnitudes of current) are measured vertically from the OX axis may be regarded as being made up of two parts, namely, (*a*) a direct component, and (*b*) an alternating component. The direct component is represented at any instant by the ordinates to the curve AB or at the time X by the ordinate GH. The alternating component is a wave whose crest value is the difference between the ordinates to the curve CD and AB. This difference at the time X has the value HJ. The effective or R.M.S. values of this alternating component are shown in the curve ST. At any instant this component is considered as having the same R.M.S. value as an alternating wave of constant amplitude whose crest value is represented by one-half the distances between CD and EF.

If I_0 is the initial effective value of the alternating component, then its initial crest value is $\sqrt{2}I_0$. The initial value of the direct component is equal to the crest value of the alternating component, and the maximum possible instantaneous value of the current, which occurs approximately at the end of one-half cycle after the short circuit, being the sum of the direct component and the crest value of the alternating component, is thus equal to $2\sqrt{2}I_0$.

The effective or root-mean-square value of the total current wave under short circuit at any instant is equal to the square root of the sum of the squares of the effective value of the alternating component at that instant and the direct component, and is represented by the curve RT. It is thus equal to $\sqrt{I_0^2+(\sqrt{2}I_0)^2}=\sqrt{3}I_0$ or 1.73 times the R.M.S. value of the corresponding symmetrical current wave.

The sustained short-circuit current is, as previously stated, limited by the synchronous impedance, or, less exactly, by the synchronous reactance, of the generator, and, neglecting saturation, it is directly proportional to the field exciting current. Although synchronous reactance is a fictitious quantity, expressing as it does in a single quantity both the armature reaction and the armature self-induction or reactance, it, nevertheless, represents the equivalent of a true reactance and may be expressed in ohms and taken just as any other reactance in determining the sustained short-circuit current. It can also be combined in the ordinary way with any external reactance.

When alternators are equipped with automatic voltage regulators the effect of the latter is to increase the excitation after a short circuit in the endeavor to hold normal voltage on the bus-bars. Any increase in excitation due to the action of the regulator will produce a proportional increase in armature short-circuit current providing the flux density

in the iron of the alternator remains below saturation. The maximum voltage which can be obtained from the exciters will not ordinarily be more than 50 per cent greater than that required at full load, 80 per cent power-factor on the alternators. Hence, the sustained short-circuit current for a short at the generator terminals will be approximately 50 per cent greater than the sustained current due to full-load, 80 per cent power-factor excitation.

An appreciable time is required for the excitation to increase to its maximum value. During the first half second the amount of short-circuit current is not appreciably affected by the presence of the voltage

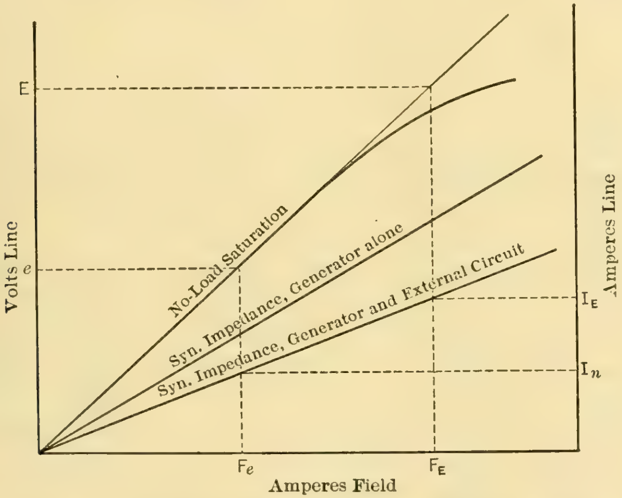


Fig. 175.—Saturation and Synchronous Impedance Curves.

regulator, but from this time on the current curve is higher, reaching a value at the end of two to three seconds approximately 50 per cent greater than that obtained without the regulator. An exception to the above appears when the external reactance is so high and the short-circuit current, therefore, so limited that the regulator is able to maintain normal voltage at the generator terminals. In such cases the sustained current may not be increased as much as 50 per cent, but will be limited to the current which will pass through the external reactance with normal voltage impressed upon it.

The per cent synchronous reactance is determined from the saturation and synchronous impedance curves, Fig. 175, as follows:

In order to produce the normal current I_n, a field current F_e is required, which would cause an open-circuit voltage e. A field current

F_E would produce an open circuit a normal voltage E if there were no saturation. Hence, e is consumed in the synchronous reactance with normal current flowing, and the per cent synchronous reactance is

$$X_s = \frac{e}{E} \times 100 = \frac{F_e}{F_E} \times 100.$$

This, combined with the per cent reactance and resistance of the external circuit, will give the sustained short-circuit current I_E, corresponding to the field current F_E, and it is then only necessary to increase I_E in the ratio of the actual field current on the alternator at the time of short circuit to F_E. That is, the sustained short-circuit current at load excitation F_1 is

$$I = \frac{F_1}{F_E} \times I_E.$$

If a voltage regulator is used, the generator field current corresponding to the maximum voltage across the collector rings must be taken as F_1.

For water-wheel driven alternators the sustained short-circuit current based on full-load excitation is generally from two to three times the normal full-load current.

When a short circuit takes place the current becomes lagging and its effect will be to demagnetize the field poles. Assume, for example, a generator with short-circuit current ratio of ten times the normal full-load current. Then tan $\phi = 10$ and $\phi = 84.5°$. Thus cos ϕ or the power factor under short circuit is equal to 0.09. However, it requires an appreciable time to reduce the magnetic flux to its low short-circuit value, since it is surrounded by the field coils, which act as a short-circuited secondary opposing a rapid change in the field flux; that is, in the moment when the short circuit starts it begins to demagnetize the field, and the magnetic field flux, therefore, begins to decrease. In decreasing, however, it generates an E.M.F. in the field coils, which opposes the change of field flux, that is, increases the field current so as to momentarily maintain the full field flux against the armature reaction. The field flux, however, gradually decreases, as does also the field current, which increased considerably the first moment. This is clearly illustrated in the oscillograms shown in Fig. 173.

Armature Connections. Synchronous generators may, as previously mentioned, be connected either single-phase, two-phase or three-phase. Single-phase machines are rarely used, and when two-phase machines are required it is, as a rule, in connection with some existing system. Three-phase machines, on the other hand, are used almost exclusively, due to the many advantages of this system over the other two.

A three-phase current may be obtained from an ordinary closed

coil winding by making connections to points on the winding spaced 120° apart, as in Fig. 176. Such a method is, however, rarely used, because the E.M.F's. of the sections, which are combined with each other to form one-phase of the three-phase circuit, are out of phase with each other, and the resultant E.M.F. and, consequently, the capacity of the machine is reduced, simply because the most effective use of the

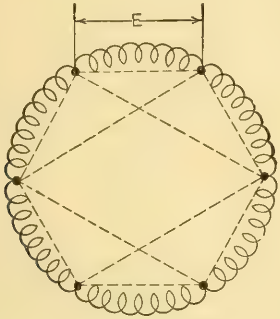


Fig. 176

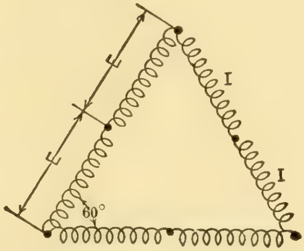


Fig. 177.

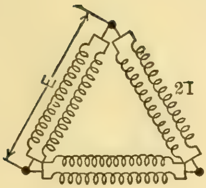


Fig. 178.

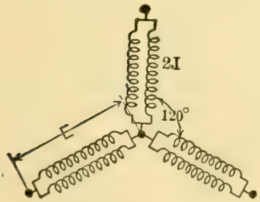


Fig. 180.

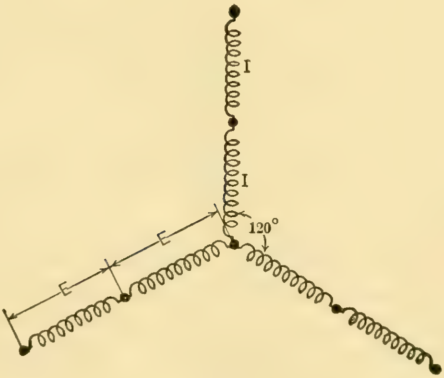


Fig. 179.

windings is not obtained. The highest output is, however, obtained with the delta and star connections where groups of similar phase relations are connected in series or parallel as in Figs. 177 to 180. Of these, however, the star connection is preferred, the main advantages of this connection being:

1. It is possible to bring out a lead from the neutral point, which is useful for various purposes.

2. The cost is less than with delta connection, requiring approximately only 58 per cent of the turns.

3. It is not possible for circulating currents of triple frequency to flow in the windings.

If E represents the effective E.M.F. of each group and I the limiting current which can be carried by the same, the corresponding three-phase capacities of the various arrangements will be

Fig. 176: $3 \times \sqrt{3}E \times I = 5.196EI$;

Fig. 177: $3 \times 2E \times I = 6EI$;

Fig. 178: $3 \times 2I \times E = 6EI$;

Fig. 179: $2\sqrt{3}E \times I \times \sqrt{3} = 6EI$;

Fig. 180: $\sqrt{3}E \times 2I \times \sqrt{3} = 6EI$.

For two-phase connections the capacities are the same for the different combinations shown in Figs. 181 to 184. If E_1 represents the E.M.F. of each group and I the permissible current it equals $4E_1I$.

The armature winding of single-phase generators can be arranged either for purely single-phase duty or on the basis of the same winding being used both for polyphase and single-phase service, the latter method being the one mostly used. When intended for three- and single-phase service any one of the connections shown in Figs. 185 to 187 can be used, although the star connection in Fig. 187 is by far the most common.

The single-phase E.M.F's. will be the same as three-phase with the exception of the arrangement shown in Fig. 186, where the single-phase connection is obtained from diametrically opposite points on the closed-coil winding.

The comparative capacities of the machines when used for single-phase and three-phase service should obviously be based on the losses and heating in the individual armature coils or group of coils and not on the total armature losses. The reason for this is that the armature loss is not equally divided among the different groups of coils and the heating therein will consequently be higher in groups carrying the highest current. When a polyphase machine, therefore, is loaded single-phase, its capacity is limited by the current which any individual coil can carry, and this current is obviously the same whether polyphase or single-phase.

With the connection as shown in Fig. 185, the three-phase rating is the same as in Fig. 176; viz., $3 \times \sqrt{3}E \times I$, or equal to $5.196EI$. The corresponding single-phase rating is $\sqrt{3}E \times 1.5I$ or equal to $2.598E$;

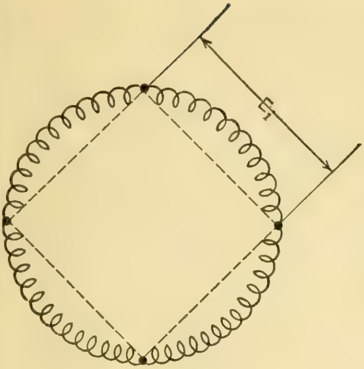


FIG. 181.

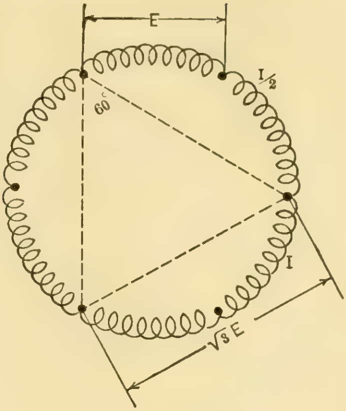


FIG. 185.

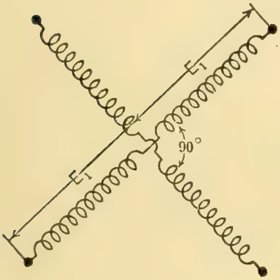


FIG. 182.

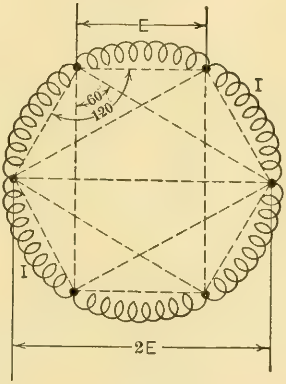


FIG. 186.

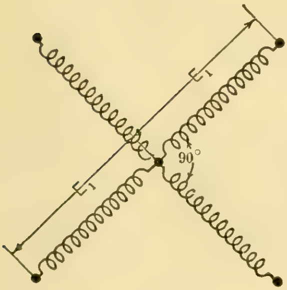


FIG. 183.

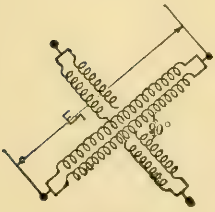


FIG. 184.

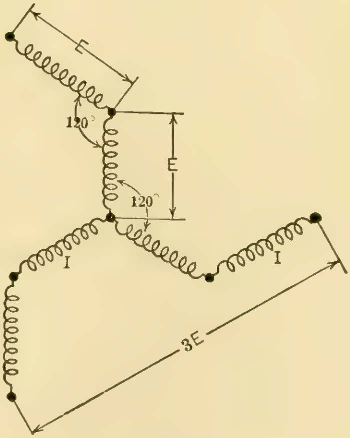


FIG. 187.

the two groups of the winding carrying the limiting current I while the other four groups carry a current equal to $\frac{I}{2}$, the total current thus being $1.5I$. The single-phase capacity with this connection is, therefore, equal to 50 per cent of the corresponding three-phase rating.

The diametrical connection shown in Fig. 186 gives a much higher rating than the previous one. The relative capacities, however, depend on whether the six terminals are utilized in connection with transformers for obtaining three-phase power. As each half of the winding can carry the limiting current I, the total current is equal to $2I$, and the single phase rating $4EI$, the single-phase E.M.F. being $2E$. The corresponding six-phase rating is equal to $6EI$, and the single-phase rating is, therefore, 66.7 per cent of this rating. For straight three-phase connection, however, the three-phase rating becomes $5.196EI$ and in this case the single-phase capacity is 77 per cent of the three-phase.

With star connection shown in Fig. 187, two of the phases carry all of the current while the third phase is idle and could be omitted, although it is generally added, being a reserve in case of accident to either of the other phases. With the star arrangement, as shown, two-thirds of the winding is almost in phase with the single-phase terminal E.M.F., being 86.6 per cent effective, and this arrangement is, therefore, about 15 per cent more effective than the delta connection shown in Fig. 185.

The three-phase rating is $3E \times I \times \sqrt{3}$ or equal to $5.196EI$, while the single-phase rating is equal to $3EI$; thus 57.7 per cent of the three-phase rating. This is by far the most common method of connecting armature windings for single-phase service.

The general practice in building single-phase generators is to use a Y-wound stator and give it a rating from 65 per cent to 70 per cent of the three-phase rating. This is possible, since one-third of the armature slots will either be vacant or filled with coils in which no current is flowing, and so serve to carry away the heat from the two-thirds of the stator in which there is current.

With two-phase alternators, single-phase current may be taken off from two of the terminals, and assuming the same limiting current I per coil and a coil E.M.F. E_1, we get the single-phase capacity for Fig. 181, $\sqrt{2}E_1 \times 2I$, or equal to $2.828E_1I$ which is 70.7 per cent of the corresponding two-phase rating $4E_1I$.

For the arrangements shown in diagrams Figs. 182 to 184, the single-phase rating will be equal to $2E_1I$, while for Figs. 188 and 189 it will equal $2.828E_1I$.

A comparison of the two-phase and three-phase capacities both with

respect to each other and to the single-phase ratings obtained is readily made. As E_1 is equal to $\sqrt{2} \times E$, the two-phase ratings $4E_1I$, when put in terms of three-phase, will be $4 \times \sqrt{2} \times E \times I$ or equal to $5.656EI$. When comparing this with the ratings obtained from the various arrangements given on page 298, it is seen that the three-phase closed-coil arrangement gives less output than for two-phase, while the other three-phase arrangements give an increased rating.

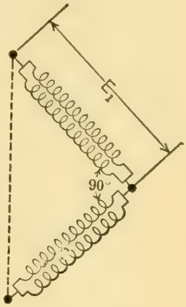


FIG. 188.

The best single-phase rating obtained from a three-phase winding occurred with the closed-coil arrangement, Fig. 186, and was equal to $4EI$. For a two-phase winding, on the other hand, the best single-phase rating was shown to be equal to $2.828E_1I$. As E_1 is equal to $\sqrt{2}E$, this equals $2.828 \times \sqrt{2} \times E \times I$, or $4EI$; thus the same as with closed-coil winding, shown in Fig. 186.

The above capacities, as previously stated, have reference only to machines which can be adapted to both polyphase and single-phase service. For machines designed for purely single-phase duty, the ratings can, however, be somewhat higher. This is due to the fact that the armature winding can be more efficiently spaced and proportioned, in which case the limit in output as a rule is determined by the temperature rise in the field.

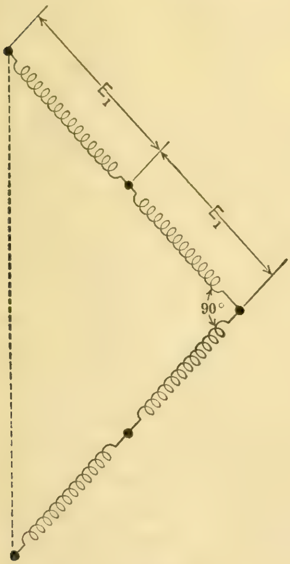


FIG. 189.

Wave Shape. The E.M.F. in a conductor is proportional to the rate of cutting the lines of force, and has, therefore, a wave form of the same shape as the curve of flux distribution. Due to the non-uniform flux distribution in definite pole machines, caused by the slots, the shapes of the pole-pieces, the armature reaction, etc., the wave will never have a perfect sine shape. It may, however, be considered as the resultant of a number of sine waves consisting of a fundamental and harmonics. The third and fifth harmonics are generally predominating in three-phase machines, while even harmonics are seldom found in the E.M.F. wave of an alternator. This is due to the fact that the resultant of a fundamental and an even harmonic gives an unsym-

metrical curve, as shown in Fig. 190, where the resultant curve is made up of a fundamental and a second harmonic. If, therefore, the E.M.F. wave is symmetrical, it may be assumed that no even harmonics are present.

With fractional pitch-windings certain harmonics are eliminated, depending on the pitch. For example, if the pitch of the coil can be shortened by $\frac{1}{n}$ of the pole pitch, then the nth harmonic and its multiples will be eliminated.

The analysis of a wave involves a considerable amount of work, but, in general, it is possible to tell at a glance which harmonics are predominating. With a positive third harmonic, that is, if counting from the zero point of the complex wave the harmonic wave rises, the complex wave will be flat-topped. If, however, the harmonic is negative, that is, if after crossing the base line, it rises in opposition to the complex wave, its effect will be to produce a distorted wave of the peaked type. A fifth harmonic, however, if positive, will give rise to a peaked saw-toothed wave, and if negative to a flat-topped wave.

Fig. 190.—Unsymmetrical Distorted E.M.F. Wave.

Complex alternating current waves, as mentioned above, can be represented by their equivalent sine wave, having the same effect as the complex wave. They have the same effective value, that is, the same square root of mean square of the instantaneous values as the complex wave. Thus, considering all complex alternating currents as represented by equivalent sine waves, all investigations become applicable to any alternating current circuit, irrespective of the wave shape. Terms such as reactance, impedance, etc., are based on the assumption of a sine wave or equivalent sine wave.

The objections to higher harmonics are, among other things, their effect in increasing the maximum value of the E.M.F. and the correspondingly increased insulation strain, as shown by the peaked waves in Fig. 191. In certain cases the triple frequency voltage established by the generator is of sufficient value to cause heavy triple frequency currents to circulate. A considerable distortion of wave shape might also affect the performance of induction or synchronous motors. Here, if the distortion of the voltage wave acting at the motor terminals is considerable, the rotating field produced will be more or less of a pulsating character. Induction motors might operate uneconomically

with a possibility of dead points in the starting torque, or with a considerable counter torque during running. Synchronous motors or converters may hunt, or even fall out of step. Or if the wave shape of the induced counter electro-motive force greatly differs from the pressure wave acting at the terminals of a synchronous motor or converter, excessive heating might result, thus lowering the efficiency of the system. These results are, of course, to be expected only if the distortion is considerable, and for this reason it has become a general practice to limit the maximum permissible deviation of the complex wave from a true sine wave to 10 per cent. This deviation is to be determined by superimposing upon the actual wave, as measured by an oscillograph, the equivalent sine wave of equal length, in such a manner as to give the

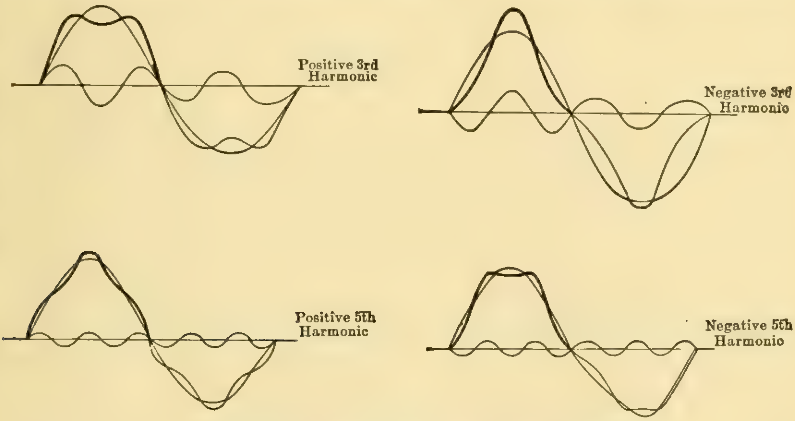


FIG. 191.—Symmetrical Distorted E.M.F. Waves.

least difference, and then dividing the maximum difference between corresponding ordinates by the maximum value of the equivalent sine wave.

For three-phase machines the three circuits are, as previously stated, connected either in star or delta. The line voltages of the three phases are 120° apart and their sum must, at any instant, be zero. Since the third harmonics are in phase with each other, they would not add up to zero and, therefore, cannot exist; and for the same reason a third harmonic of the line current cannot be present. In a balanced system, third harmonics can exist only in the voltage from line to neutral or Y-voltage, and in the current from line to line or delta current, as will be explained in the following.

Figure 192 represents a delta-connected three-phase generator with a predominating third harmonic E.M.F. in each phase. As the

three triple harmonics are in phase, the machine is really running under short circuit, as far as the triple harmonic is concerned. This triple-frequency current is internal in the windings, and the E.M.F's. which cause it to flow are short-circuited in the closed delta, and will, therefore, not appear in the terminal E.M.F's. The circulating current may be of great magnitude, entailing large I^2R losses in the windings with corresponding loss of efficiency.

If the generator is Y-connected, as in Fig. 193, the terminal E.M.F.

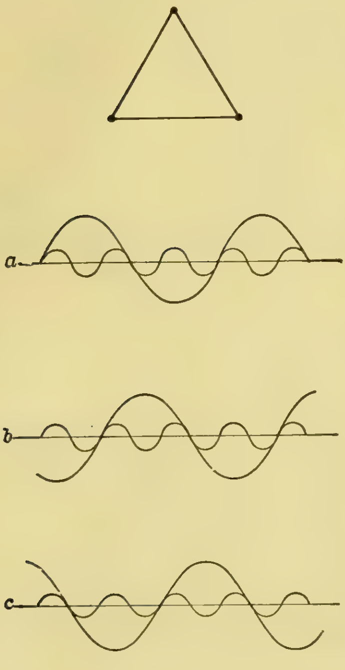


FIG. 192.

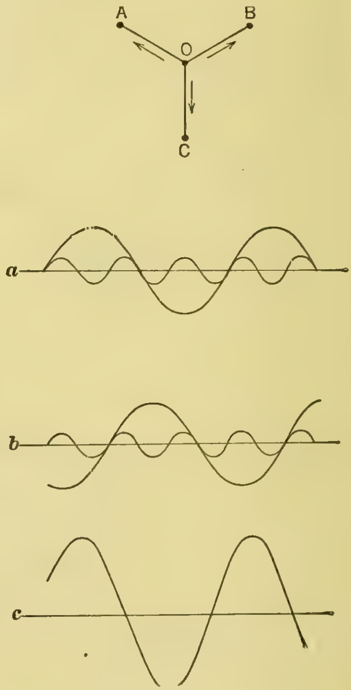


FIG. 193.

between A and B is the resultant of the two E.M.F. vectors OA and OB, thus $OA-OB$, the negative sign of the latter on account of its direction. The triple harmonics are the same as in the previous case, but by adding the E.M.F. waves in a and b, corresponding to OA and OB, we get the resultant c. OB, that is b, must, of course, be reversed and the triple harmonics will cancel and no triple harmonic can, therefore, exist in the terminal E.M.F., but the fundamental E.M.F. wave is, of course, larger than in each of the phases.

If the neutral is grounded, the potential difference from line to

ground may not be the line voltage divided by $\sqrt{3}$; but, superimposed on this voltage, there may be the triple-frequency E.M.F. and the maximum value of the wave may be greatly icreased thus increasing the insulation strain.

In a balanced three-phase system, third harmonics can, therefore, only exist in the voltage from line to neutral or Y-voltage; in the current from line to line, or generator delta current; and in the line current only if the generator neutrals are grounded or a return circuit provided.

Grounding of Generator Neutral. Present practice, even with systems where there is no local distribution, seems to indicate a very general tendency to ground the neutral of the generator winding. Such grounding stabilizes the neutral point and prevents electrostatic charges from accumulating, by providing a path for them to ground. A grounded neutral also makes it certain that the differential protective scheme, which is now being generally used with large generators, will also protect the generator from internal grounds and not only for shorts from phase to phase.

Whether the neutral should be grounded directly or through a resistance is a question which depends to a great extent on the operating conditions. With direct grounding, any other ground on the system will obviously produce a dead short circuit of that particular phase, but, on the other hand, it will prevent the voltage between lines and ground from attaining a higher value than the Y-voltage. In plants with low-voltage underground feeders there is a predominating tendency to ground the neutral through a resistance of such a value that it will limit the current which would flow with a ground on the system to about two or three times that of the normal full-load value of the highest capacity feeder. This will also permit a sufficient current flow to assure a definite selective operation of the relays; and, in case of an arcing ground, such a dynamic current would tend to make the ground permanent and the arc quite steady, thus preventing high frequency oscillations from being set up. Such oscillations, which are set up when an arc is continuously interrupted and reformed, may be very dangerous, as they will superimpose on one another and may result in very high voltages. With a sufficient current flowing through the accidental ground, the arc will usually be quite free from oscillations, and the breaker will usually trip before a short circuit between phases occurs in the cable.

In plants where the outgoing circuits are in the nature of high-voltage transmission lines, the generator neutral may well be direct-grounded, as the short-circuit currents caused by grounds in the system will then be much lower than with low-voltage feeders, owing to the

intervening impedance of the step-up transformers and the lines. This is especially true when the accidental ground occurs a long distance from the generating station.

It is general practice to ground only one generator at a time, as trouble has sometimes been experienced from circulating currents flowing between the machines when two or more units have been grounded at a time. With duplicate machines, any irregularities in the wave shape would probably be the same in all the machines, and

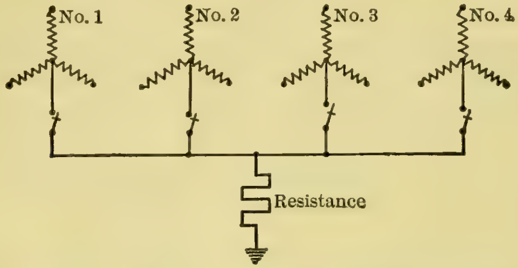


Fig. 194.—System of Grounding Generator Neutrals.

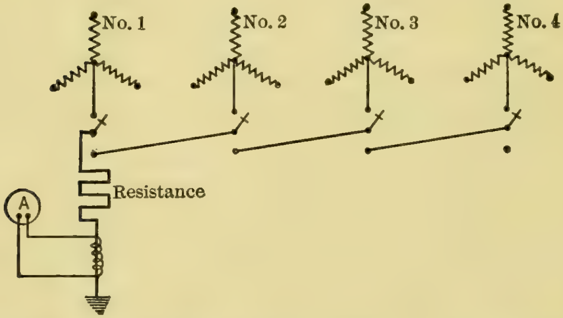


Fig. 195.—System of Grounding Generator Neutrals. (Only one neutral can be grounded at one time.)

no higher harmonic current would circulate through the neutrals. Several companies are thus operating with two or more machines grounded and with quite satisfactory results. The diagrams in Figs. 194 and 195 show connections for grounding of generator neutrals, the lower diagram giving a scheme whereby it is only possible to ground one neutral at a time. Single-pole oil circuit breakers, rather than disconnecting switches, are recommended in the ground connection, it being common practice to install breakers having a current-carrying capacity about one-fourth of the normal generator capacity. The

breakers should also, of course, have a sufficient short-time carrying capacity to safely carry any short-circuit currents.

Rating. Synchronous generators should be rated by the electrical output, and this should be expressed in kilo-volt-amperes (kv.a.) and not in kilowatts (kw.) unless the power factor of the load is also given. Preferably both should be given, so as to avoid any misunderstanding whether kv.a. or kw. is meant, for example 2000 kv.a. (1600 kw.—.8 P.F.).

Most water-wheel-driven generators are now given a maximum continuous rating, without any overload provision, except that they must be able to carry momentary loads of 150 per cent of the amperes corresponding to the continuous rating, keeping the rheostat set for load excitation.

The rated full-load current is that current which, with rated voltage, gives the rated kilowatts or rated kilo-volt-amperes. In machines in which the rated voltage differs from the no-load voltage, the rated current should refer to the former. The rated output may be determined as follows:

If E = full-load terminal voltage and I = rated current, then for a single-phase generator

$$\text{kv.a.} = \frac{EI}{1000}.$$

For a two-phase generator, the total output is equal to the output of the two single-phase circuits, and if I, in this case, is the rated current per circuit, the output for a two-phase generator is

$$\text{kv.a.} = \frac{2EI}{1000}.$$

For a three-phase generator there are three circuits to be considered, whether the machine is star or delta connected. If E is the terminal voltage and I the line current, then for a three-phase generator

$$\text{kv.a.} = \frac{3EI}{\sqrt{3} \times 1000} = \frac{\sqrt{3}EI}{1000}.$$

The rating of a generator is usually determined by the permissible temperature rise caused by the current. This rise necessarily increases with increasing load and also with decreasing power-factor. Thus, for a given kv.a. output, the total heat losses are larger for low than for high power factors, the difference being due to the heat generated by the increased field current, which is required to overcome the armature reaction and maintain the given current and terminal voltage.

Alternating-current generators are generally designed to operate with a normal load and 80 per cent power factor without exceeding a specified temperature rise; and should such a machine have to be operated with a load having a lower power factor, its rating will be reduced when based on the same temperature guarantee. The true operating power factor should, therefore, be carefully considered in selecting the capacity of the generating units. The power factor depends not only on the type of apparatus comprising the load, but also on the load factor at which the units are operated.

To obtain the total kv.a. capacity of a system, the sum of the wattless components of the different loads should be calculated, the efficiency, power factor and load factor being duly considered. The total capacity is then equal in kv.a. to

$$\sqrt{(\text{Total kw. energy})^2+(\text{Total kv.a. wattless})^2},$$

and the combined power factor of the load

$$=\frac{\text{Total kw. energy}}{\text{Total kv.a.}}.$$

It is obvious that a generator must not be operated under conditions conducive to excessive temperatures which will cause the insulation to deteriorate. The limitations, for this country, are generally governed by the A.I.E.E. Standardization Rules. These rules, which are the result of many years of the widest practical experience and tests, use as a basis certain "hottest-spot" temperatures for various classes of insulation, and limiting "observable" temperatures are deduced from these limiting "hottest-spot" temperatures by subtracting therefrom a "conventional allowance," this being a specified number of degrees which thus represents a margin of security between the limiting hottest spot and the limiting observable temperatures.

The insulation materials usually employed in electrical power machinery are classified as follows:

Class A. Cotton, silk, paper and similar materials, when so treated or impregnated as to increase the thermal limit, or when permanently immersed in oil; also enameled wire.

Class B. Mica, asbestos and other materials capable of resisting high temperatures, in which any Class A material or binder is used for structural purposes only, and may be destroyed without impairing the insulation or mechanical qualities of the insulation.

The limiting "hottest-spot" temperature for Class A material is

standardized by the Rules as 105° C., and for Class B as 125° C. If different insulating materials are used on various parts of one winding, as for example in the slot and for the end windings, the temperature of each material shall not exceed the limit set for that material. Similarly, when insulation consists of layers of materials having different temperature limits, for instance high-temperature limit material adjacent to the copper and lower-temperature limit material adjacent to the iron or to the air, the temperature of each material shall not exceed the limit set for that material.

There are three fundamental methods of making temperature measurements. These are designated as Methods 1, 2 and 3, and are defined in the Rules as follows:

Method 1.—*Thermometer Method.* This method consists in the measurement of the temperature, by mercury or alcohol thermometers, by resistance thermometers, or by thermo-couples, any of these instruments being applied to the hottest accessible part of the completed machine. This method does not include the use of thermo-couples or resistance coils imbedded in the machine as described under Method 3.

Method 2.—*Resistance Method.* This method consists in the measurement of the temperature of windings by their increase in resistance. In the application of this method, thermometer measurements shall also be made whenever practicable without disassembling the machine, in order to increase the probability of obtaining the highest observable temperature. The measurement indicating the higher temperature shall be taken as the " observable " temperature.

Method 3.—*Imbedded Temperature—Detector Method.* This method consists in the measurement of the temperature by thermo-couple or resistance temperature detectors, located, as nearly as possible, at the estimated hottest spot. When Method 3 is used, it shall, when required, be checked by Method 2. The highest observable temperature obtained from the readings of the imbedded detectors shall not exceed the values permitted by the Rules for Method 3, and the highest observable temperature obtained by Method 2 shall not exceed the values permitted by the Rules for Method 2.

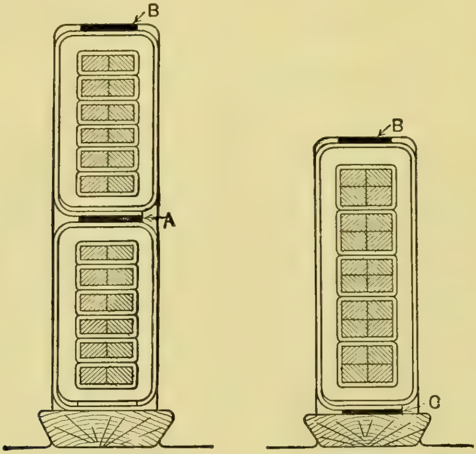
The specified " conventional allowances," or differences by which the " observable temperatures " are assumed to be lower than the " hottest-spot " temperatures, are for:

Method 1—15° C.
Method 2—10° C.
Method 3—as follows:

For windings with two coil-sides per slot, with detectors between top and bottom coil-sides (and between coil-sides and core) Fig. 196A	5° C.
For windings with one coil-side per slot for 5000 volts or less, with detectors between coil-side and core between coil-side and wedge. Fig. 196B.	10° C.
For windings with one coil-side per slot for more than 5000 volts, with detectors between coil-side and core and between coil-side and wedge. Fig. 196B.	10° C.+1° C. for every kv. of terminal pressure of the machine above 5 kv.

For resistance measurements, the temperature coefficient of copper may be deducted from the formula

$$\frac{1}{(234.5+t)}.$$



a. Double-layer Winding. *b*. Single-layer Winding.

Fig. 196.—Methods of Locating Temperature Detectors.

Thus, at an initial temperature $t=40°$ C., the temperature coefficient of increase in resistance per degree Centigrade rise, is

$$\frac{1}{(274.5)}=0.00364.$$

Table XLIII, deduced from the formula, is given for convenience of reference.

TABLE XLIII

TEMPERATURE COEFFICIENTS OF COPPER RESISTANCE

Temperature of the Winding, in ° C. at which the Initial Resistance is Measured.	Increase in resistance of Copper per ° C. per Ohm of Initial Resistance.
0	0.00427
5	0.00418
10	0.00409
15	0.00401
20	0.00393
25	0.00385
30	0.00378
35	0.00371
40	0.00364

The limiting observable temperatures for use with Methods 1, 2 and 3 are, therefore, arrived at by subtracting the "conventional allowances" from the limiting "hottest-spot" temperatures, and are as given in Table XLIV.

TABLE XLIV

LIMITING OBSERVABLE TEMPERATURES

		Class A Material.	Class B Material.
Method 1		90° C.	110° C.
Method 2		95° C.	115° C.
Method 3	For windings with two coil-sides per slot, with detectors between top and bottom coil-sides and between coil-sides and core	100° C.	120° C.
	For windings with one coil-side per slot, with detectors between coil-side and core and between coil-side and wedge	95° C. (minus 1 degree for every 1000 volts of terminal pressure of the machine above 5000 volts)	115° C. (minus 1 degree for every 1000 volts of terminal pressure of the machine above 5000 volts)

The standard ambient temperature of reference for air is 40° C., and this should apply to all conditions where the actual ambient tempera-

TABLE XLV

LIMITING OBSERVABLE TEMPERATURE RISES, CLASS A INSULATION—40° C. AMBIENT TEMPERATURE

	Items.	Method 1.	Method 2.	Method 3.	
				For windings with two coil-sides per slot with detectors between top and bottom coil-sides and between coil-sides and core.	For windings with one coil-side per slot, with detectors against core and against wedge.
Windings on Stators	1. Insulated windings others than 2 and 3	50° C.	55° C.	60° C.	55° C. (minus 1° for every 1000 volts by which the terminal pressure of the machine exceeds 5000 volts)
	2. Single-layer field windings with exposed surfaces uninsulated	60° C.	60° C.		
	3. Short-circuited insulated windings	60° C.			
Windings on Rotors	4. Field windings (other than 5)		55° C.		
	5. Single layer field windings with exposed surfaces uninsulated	60° C.	60° C.		
	6. Windings in slots	55° C.	55° C.		
	7. Short-circuited insulated windings	60° C.			

For Class B insulation, use 20° C. higher values.

ture does not exceed it. Based on an ambient temperature of 40° C. and Class A insulation, the limiting observable temperature rises are as given in Table XLV.

Method 3 shall be applied to all stators of machines with cores having a width 50 cm. and over. It shall also be applied to all machines of 5000 volts and above if of over 500 kv.a., regardless of core width.

A machine may be tested at any convenient ambient temperature, preferably not below 10° C., but whatever be the value of this ambient temperature, the permissible temperature rises must not exceed those given in Table XLV.

As seen from the table, when thermometers are applied directly to the surfaces of bare windings, such as edgewise strip conductor, or a cast copper winding, the limiting observable temperature rise can be 10° C. higher than for insulated windings. For commutators, collector rings, or bare metallic surfaces not forming part of a winding, the limiting observable temperature can be 15° C. higher.

Increased altitude has the effect of increasing the temperature rise of some types of machinery. In the absence of information in regard to the height above sea level at which the machine is intended to work in ordinary service, this height is assumed not to exceed 1000 meters (3300 feet). For machinery operating at an altitude of 1000 meters or less, a test at any altitude less than 1000 meters is satisfactory, and no correction shall be applied to the observed temperature. Machines intended for operation at higher altitudes shall be regarded as special; and when a machine is intended for service at altitudes above 1000 meters (3300 feet) the permissible temperature rise at sea level shall be reduced by 1 per cent for each 100 meters (330 feet) by which the altitude exceeds 1000 meters.

Efficiency. The efficiency of a generator is the ratio of the kilowatt output to the kilowatt input at the rated kv.a. and power factor. The difference between these two quantities is equal to the losses. The method commonly and most readily used for obtaining the efficiency is to determine these losses and then compute the efficiency by dividing the power output by the sum of the power output plus the losses. This is termed conventional efficiency.

The guaranteed efficiency should always refer to the energy load, and it is most important that the power factor of the load be also given. In certain cases the guaranteed efficiency is based on a kv.a. output, but the inconsistency of such a method is apparent, as the following example will illustrate:

Assume a generator rated 100 kv.a. (100 kw. 1.0 P.F.) or 100 kv.a.

(80 kw. 0.8 P.F.), and that the losses at unity and 80 per cent power factors are 10 and 11 kw. respectively; the efficiency is then:

Based on 100 kw. 1.0 P.F.

$$\text{Eff.}=\frac{100}{100+10}=91 \text{ per cent.}$$

Based on 80 kw. 0.8 P.F.

$$\text{Eff.}=\frac{80}{80+11}=88 \text{ per cent.}$$

Based on 100 kv.a. 0.8 P.F.

$$\text{Eff.}=\frac{100}{100+11}=90 \text{ per cent.}$$

From the last two values it is seen that for 80 per cent power factor, if based on the kv.a., a 2 per cent greater efficiency guarantee can be made, although this value has no meaning, as it is based on apparent power.

It is, of course, equally important that all the losses be included and that they be figured on the same basis, in order that a fair comparison may be made of the efficiencies guaranteed by different manufacturers.

The A.I.E.E. Standardization Rules require that for synchronous generators the following losses are included in determining the efficiency: (1) core losses, (2) I^2R loss in all windings based upon rated kv.a. and power factor, (3) stray load losses, (4) friction of bearings and windage, (5) rheostat losses corresponding to rated kv.a. and power factor.

Bearing Friction and Windage may be determined as follows: Drive the machine from an independent motor, the output of which shall be suitably determined. The machine under test shall have the brushes removed and shall not be excited. This output represents the bearing friction and windage of the machine under test.

Brush Friction of Commutator and Collector Rings. The brushes shall be in contact with the commutator or collector rings, but the machine shall not be excited. The difference between the output obtained when driving the machine in this manner and the output in the previous test shall be taken as the brush friction. This is, however, negligible for water-wheel-driven generators.

Core Loss. Follow the test for bearing friction and windage, with an additional reading taken with the machine separately excited so as to produce at the terminals a voltage corresponding to the calculated internal voltage for the load under consideration. The difference

between the output obtained by this test and that obtained by the test for bearing friction and windage, shall be taken as the core loss.

I^2R Loss may be calculated directly from the resistance measurement, the current being based on the rated kv.a. and power factor. The resistance of the windings should be taken at 75° C., or the values corrected for this temperature. It is important that this direction be followed.

Brush Contact I_2R Loss. One volt per brush is the A.I.E.E. standard drop corresponding to the I^2R brush-contact loss, for carbon and graphite brushes with pigtails attached. Without pigtails, $1\frac{1}{2}$ volts per brush should be allowed. The brush-contact loss is a negligible quantity.

Stray Load Losses. These include iron losses, and eddy-current losses in the copper, due to fluxes varying with load and also to saturation.

Stray load losses are determined by operating the machine on short circuit and at rated-load current. This, after deducting the windage and friction and I^2R loss, gives the stray load loss for polyphase generators.

Field-Rheostat Losses shall be included in the generator losses where there is a field rheostat in series with the field magnets of the generator, even when the machine is separately excited.

In making efficiency tests after installation in the power station, it may occasionally be possible to drive the unit by its exciter when the same is direct-connected; but for large units and when the direct-connected exciters are not provided, the retardation or deceleration testing method is resorted to. This test is based on the principle that every moving body possesses a certain definite amount of energy, due to its motion. It is described in detail in an article by Mr. R. Treat in the *General Electric Review* for June, 1916.

A convenient and most satisfactory method of determining the efficiency of a generator after installation may be employed where there are two or more units in the power-house available for the use of the test, or where the unit under test may be varied in conjunction with some other unit of sufficient size located elsewhere in the system but which may be segregated for the purpose. The method for determining the core losses and on friction-windage losses consists in operating the generator as a synchronous motor and measuring the input by wattmeters.

When the retardation method of testing is used, it is to be recommended, if possible, to check such tests by means of the input method.

A new method of artificially loading generators for tests in hydro-

electric power stations is described in an article in the *General Electric Review* for April, 1917.

Speed. The speed of water-wheel-driven generators varies over a wide range and is determined by the frequency of the system and by the hydraulic condition, that is, the speed of the wheel, which, in turn, is governed by the size of the unit and the head. For large units the speed may thus be as low as 50 R.P.M. and as high as 750.

With a fixed frequency, the number of poles must be increased in inverse proportion to a reduction in the speed. To accommodate this increased number of poles, the diameter must necessarily be larger, and with this follows also an increased amount of material and labor. The cost of slow-speed machines must, therefore, necessarily be much higher than for machines of higer speeds.

With the materials generally used, there is naturally a limit to the permissible peripheral speeds; and in order to provide a sufficient margin in the design, based on the required over-speed of 80–100 per cent, large machines generally become quite long in the direction of the shaft. A high-speed rotor is, as a rule, much more difficult to construct than a slow-speed rotor.

Voltage. Standard generator voltages for all frequencies are 240, 480, 600, 2300, 4000, 6600, with the corresponding motor voltages 220, 440, 550, 2200, 6000. There is no motor voltage corresponding to 4000 volts, since this is only used on three-phase, four-wire lighting distributing systems. In addition, 11,000 volts is also considered standard, while 12,000 and 13,200 volts are occasionally used.

When a generator is wound for 240 volts, it does not necessarily follow that it may be reconnected for 480 volts; and, vice versa, a 480-volt machine cannot always be reconnected to 240 volts by changing the number of circuits. The above is particularly true of generators with large diameters and a great number of poles. Small machines with few poles can, as a rule, be reconnected or rewound for any voltage up to and including 2300. It is a common but erroneous idea that machines wound for 2300 volts, delta connected, can be simply reconnected to 4000 volts Y. While this is all right so far as mere voltage is concerned, the slot in the armature may not be large enough to accommodate the extra insulation required for the higher voltage. In large machines the above change may sometimes be made without much difficulty, but small machines require, as a rule, new coils and frequently new punchings.

Parallel Operation. In order that an alternating-current generator shall be able to carry a load, a current corresponding to this load must flow. The E.M.F. required to generate this current is the

resultant of the terminal and the induced E.M.F's. of the generator, the displacement between these E.M.F's. being due to the impulse of the prime mover. In the same manner, when two or more generators are operating in parallel, the division in load between the different units is entirely dependent on the turning efforts of the prime movers, and a change in the field excitation, as with direct-current generators, will have no effect whatsoever.

For a satisfactory parallel operation, it is important that the E.M.F's. of the generators be the same and that they be operated in perfect synchronism, as, if this is not the case, cross currents will flow between the units. These cross currents may be wattless, or they may represent a transfer of energy, depending on whether they are caused by a difference in the E.M.F. or a speed variation of the machines.

When two alternators are operating in parallel at the same speed, their E.M.F's. are naturally in opposition, as shown in Fig. 197.

Let *OA* be the E.M.F. of generator No. 1 and *OB* the E.M.F. of generator No. 2, the difference in their values being caused by a stronger excitation of the latter machine. The resultant E.M.F., *OC*, will be in phase with *OB*, and, being impressed on the synchronous impedance of the two generator armatures in series, it will produce a cross current, lagging nearly 90° behind the E.M.F. of generator No. 2 and leading nearly 90° in advance of the E.M.F. of generator No. 1. This is practically true, as the impedance can be considered to consist almost entirely of the reactance of the circuit. The cross current will, therefore, have a magnetizing effect on generator No. 1 and a demagnetizing effect on generator No. 2, and consequently keep the voltages the same. The cross current is wattless, consuming no power except that corresponding to the I^2R loss in the circuit. It is thus evident from the above that a change in the field excitation can have no effect on the load of the machine.

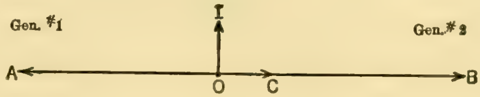


Fig. 197.

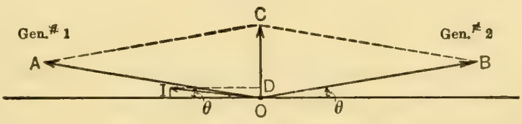


Fig. 198.

If the excitation of the two machines is the same, but the governor adjustments differ, a cross current will also be produced, as shown in Fig. 198. *OA* represents the induced E.M.F. of generator No. 1, leading θ degrees in advance of the busbar voltage, while *OB* represents the induced E.M.F. of generator No. 2, lagging θ degrees behind the

busbar voltage. The resultant, OC, will cause a cross current to flow, and as the resistance of the circuit is small compared to the reactance, it will lag nearly 90° behind OC, and will practically be in phase with the E.M.F. of generator No. 1, and in opposition to the E.M.F. of generator No. 2. It will thus consume power of the leading machine No. 1, that is, retard it, and supply power to the lagging machine No. 2, that is, accelerate it, and thus pull the two machines together. It is evident from the diagram that it is the reactive component, ID, of the cross current that produces the synchronizing power, and that the power component, OD, has no effect in this respect. A certain amount of reactance is therefore necessary for a satisfactory synchronous operation, and the larger the reactance is, compared to the resistance, the larger is the synchronizing component of the cross current. Increasing the reactance would, therefore, increase the synchronizing force; but there is a limit hereto also, as with a very high reactance the total cross current would be reduced, and thus also the synchronizing current.

The synchronizing force is a function of the short-circuit current ratio of the generator, and may be defined as the torque per degree displacement.

The torque in foot-pounds corresponding to a given kw. energy load is:

$$T=\frac{\text{kw.}\times 33{,}000}{\text{R.P.M.}\times 2\pi\times 0.746}=\frac{\text{kw.}\times 7040}{\text{R.P.M.}},$$

The synchronizing torque is then equal to

$$T_s=\frac{\text{kw.}\times 7040}{\text{R.P.M.}\times\theta},$$

where θ is the angle of displacement.

Assume a generator rated $ATB-72-1250$ kw. 1.0 P.F.$-100-$ 2300 V., having a synchronous impedance limiting the short-circuit current to three times normal. The current flowing can, with sufficient accuracy, be assumed to be proportional to the sine of the displacement between the terminal or busbar E.M.F. and the induced generator E.M.F. At short circuit, this displacement would be approximately 90°; thus the short-circuit current would correspond to sin $90°-1$. As this current has been assumed to be three times full-load current, the latter would correspond to a displacement of $\theta°$, the sine of which would be equal to $\frac{1}{3}$.

Sin $\theta=\frac{1}{3}$ and $\theta=19.5$ degrees.

The synchronizing torque of this generator with a certain displacement, for example, 10 degrees, would be:

$$T_s=\frac{1250\times 7040}{100\times 19.5}=4525 \text{ foot-pounds.}$$

The cross current of the above generator with a certain displacement, for example, 10°, would be:

Sin 10° = 0.17.

Full-load current = 315 amperes.

$$\text{Cross current}=\frac{0.17}{0.33}\times 315=160 \text{ amperes.}$$

Strictly speaking, this is not a cross current but the transfer of current to the generator in question from the others, which are relieved of a corresponding amount.

Where there is trouble from excess cross currents, it is usually found to be due to a machine that regulates too closely, having too high a short-circuit ratio in combination with insufficient flywheel capacity.

In considering the function of flywheel effect, a sharp distinction should be made between momentary speed changes or speed fluctuations and slow changes or adjustments due to the speed-load characteristic of the water wheel and governor, or what is properly called speed regulation. All prime movers that operate together to supply power to a common load must operate at a lower speed when loaded than when unloaded, in order that the several prime movers may properly divide the load. It is also well to differentiate between the function of flywheel effect in water-wheel-driven generators and in reciprocating-engine-driven generators. In the former, the single purpose is to restrain speed changes during the necessarily long period of adjustment of input to output. In the latter the most important function is to prevent the excessive changes in angular velocity during a single revolution that would otherwise be caused by the varying torque delivered by the engine cylinders. While with engine-driven units flywheel effect is important from the standpoint of steady parallel operation, this is not the case with water-wheel installations. With the latter the flywheel effect influences the speed only with sudden changes in load, and during the short time interval during which the hydraulic conditions are changing to meet the new load conditions.

The division of the load is entirely dependent on the angular displacement between the busbar and induced generator E.M.F's. caused by the turning movements of the prime movers. It is, therefore, evident that the speed regulation of the prime movers must be the same;

i.e., they must drop in speed from no load to full load by the same percentage and in the same manner. If this is not the case, the alternator connected to the prime mover of closer speed regulation will take more than its share of the load under heavy loads and less under light loads; a too close speed regulation is, therefore, not desirable for parallel operation of alternators. To illustrate this further: Assume prime movers of different speed regulation as shown in Fig. 199. It has previously been proved that, when two machines are operating in parallel, if an irregular speed exists, a transfer of energy will take place between the alternators, tending to retard the machine of the higher speed and accelerate the machine of the slower speed, thus tending to hold the machines in synchronism at a speed corresponding to the load. The division of the load between the units depends then only on the action of the governors, and it is seen from the curves that at a load c the machines will divide the load equally. For other loads, the ratio will be different; for example, at a certain lighter load the ratio may be $\frac{oa}{ob}$, while for a certain heavier load it may be $\frac{oa_1}{ob_1}$.

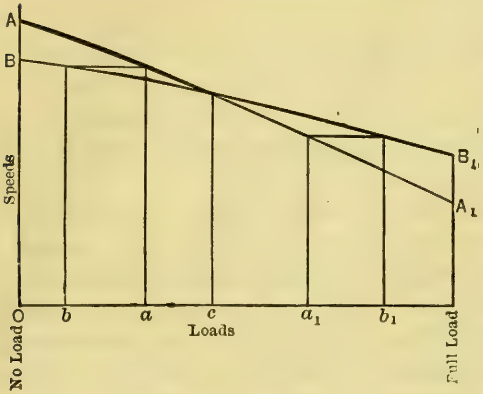


Fig. 199.

The division of load between two alternators depends, therefore, as stated, primarily upon the speed-load characteristics of the prime movers, the governors of which must be adjusted for a definite drop in speed from no load to full load. With flat speed characteristics the division of the load will be of an unstable nature. By adjusting the field, the form of the energy delivered by the generator can be changed, but not the amount. What really occurs with a change in field adjustment of any piece of synchronous apparatus operating in parallel with another, is a change of the power factor of that machine.

The above refers also to different stations operating in parallel on the same system, and the division of load and wattless current between the stations must, therefore, be handled differently. On a network supplying power over a large territory, the power factor will often

be low and there will be considerable wattless current to be taken care of.

A successful parallel operation of several stations on a system is, as a rule, not difficult, inasmuch as the line characteristics, i.e., resistance and reactance, are generally such that they interfere but little with the synchronizing force of the generators. This force is, as stated, greatest when the machines are over-excited, and the only case where a machine would drop out of step would be on extensive systems where large lagging currents are required for voltage regulation. These currents naturally greatly reduce the synchronizing force in that they weaken the field, but there is generally no danger of a shutdown unless a very heavy load should suddenly come on.

Many different methods are used for dividing and regulating the load on a large system. In some cases one or more generators in a large station, or one or more stations in a large system, will do the governing, taking care of the load, the other generators or stations being then operated with constant gate opening and constant load. Plants having large pondage are usually selected to take care of the load fluctuations, while those with little or no storage should preferably be operated so as to take the full flow of the stream. In some systems such stations are equipped with induction generators which very seldom require attention, possibly only once a day. They may be started up in the morning or kept running all the time, and as they are dependent on the other synchronous apparatus of the system for their excitation, their speed and frequency is determined by this apparatus. As there are no governing devices, means must be provided for disconnecting the units from the system, as well as shutting the gates, in order to prevent overspeed, should the load be dropped for some reason or other.

As a rule, steam-turbine stations that are used as auxiliaries carry little load under ordinary circumstances, but occasionally carry a full load of wattless current, and are always ready in case of emergency to pick up the load.

In this connection it may be well to point out the fallacy that often leads large customers to specify that their lines shall be independent of the rest of the system and that their load be supplied by separate generators. Such requirements are, of course, based on an assumption that the customer obtains a better service in this way, as his lines or generators are not affected by the fluctuation on the rest of the system. This is, however, in most instances not the case, as changes in his load will affect the speed on his generators and the regulation of his lines much more than if the fluctuations were divided among a greater number of

generators and lines. So, for example, in a large system, what would be 50 per cent load thrown on or off one generator if it were feeding a separate customer would, perhaps be only 5 or 10 per cent load on the entire system, and neither speed nor voltage would be materially affected. In general, it may, therefore, be said that in many cases it is preferable to operate everything in parallel and to have the governors on as many machines as feasible. This naturally reduces the work of the governors, as a change in load then only requires each governor to work through a small range, allowing a more sensitive adjustment and less speed deviation than there would be if the system were divided up into sections with different generators supplying individual loads.

Mechanical Design. *Revolving Field Type.* Alternating current generators are almost always of the revolving field type, this construction being preferable to the revolving armature type. Besides relieving the high potential armature winding from strains imposed by a centrifugal force, it gives an increased space for the winding, which is of greatest importance. Only two collector rings are required for handling the field current, the energy and voltage of which is relatively small compared to that which would have to be handled in the case of a revolving armature generator of the same capacity.

Method of Drive. With regard to the method of drive, water-wheel-driven generators are almost always of the direct-connected type, only the very smallest sizes being belt or rope driven. They are, in most cases, self-contained; i.e., they are supplied with shaft, bearings and base or foundation caps.

Horizontal or Vertical. Water-wheel-driven generators may be either of the horizontal or vertical type, the latter being now almost universally used for low- and medium-head installations. The choice is, however, entirely governed by the hydraulic requirements and is treated in more detail under the section on turbines.

Stator Frame. The main function of the stationary armature frame is to support the punchings, and it should, therefore, be of a rigid construction so as to prevent any sag of the punchings due to their weight and an unbalanced magnetic pull. In case of vertical units, it should also be sufficiently strong to carry the weight of the top bearing bracket, which in turn supports the generator rotor and the turbine runner.

The frame is usually made of cast iron with a box type construction. For smaller units it is made in one piece, but for larger units it is, as a rule, split in two or more parts to facilitate handling and shipping. A number of openings are provided for ventilation, a subject which is treated more in detail in the latter part of this section.

The core consists of sheet-iron laminations carefully annealed and

treated so as to minimize both hysteresis and eddy-current losses. The punchings are stacked together so that the laminations overlap each other. They are held rigidly in place by heavy steel clamping fingers, air circulation being provided for by air ducts formed by spacing blocks inserted at frequent intervals between the laminations. The outer circumference is dovetailed for fastening to the frame, while the slots for the windings are punched at the inner circumference, the slots generally being of the open type so as to permit the use of form-wound coils, which can easily be removed and replaced in case of damage.

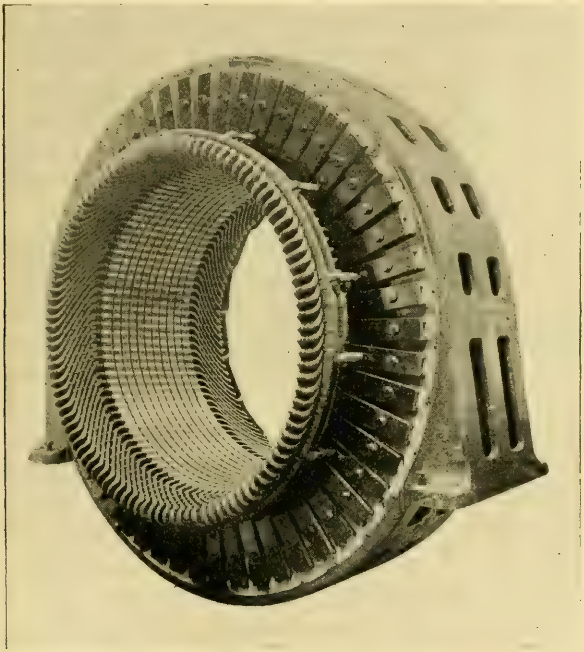


FIG. 200.—Stator Showing Lap or Barrel Type Armature Winding.

In case of very large machines with split stator frames, the laminations may be assembled in the manufacturer's shop before shipment; but in such a case the advantages of overlapping lamination joints are lost. After, the laminations are shipped separately and put in at the destination after the sections have been bolted together.

Bed plates or pads, grouted into the foundation, should always be used. With vertical units they provide an easy means of aligning the generator with the wheel by shims or adjusting bolts.

Armature Winding. The armature winding is generally of the lap or barrel-wound type, Fig. 200; the chain winding has been practi-

cally abandoned as it requires coils of different shapes, especially with the widely distributed windings which are used in modern machines.

The coils should be taped and treated with an impregnating compound, the number of layers and dippings being determined by the operating voltage. The materials used should be very carefully selected to avoid deterioration or diminution of the dielectric strength, this being especially important for high potentials.

The temperature at which the machine is to be operated has also an important bearing on the type of insulation to be used, as recognized by the A.I.E.E. Standardization Rules previously referred to. For ordinary temperatures, the insulation generally consists of varnished cambric alone or of a combination of mica and varnished cambric. For high temperatures, the all-mica insulation is generally used. In order, further, to avoid mechanical injury to the coils, when inserting them in the armature slots, they should be protected by a casing of horn, fiber or other suitable material. For large coils, this armor is generally cemented directly to the slot portion of the coil.

The coils generally consist of a number of turns of copper wire or ribbon; and where the copper section necessary to carry the current becomes too large for a single strand, the conductor is subdivided into a number of strands of small section, to facilitate the forming of the conductor in the coils and also to reduce the eddy current losses in the copper.

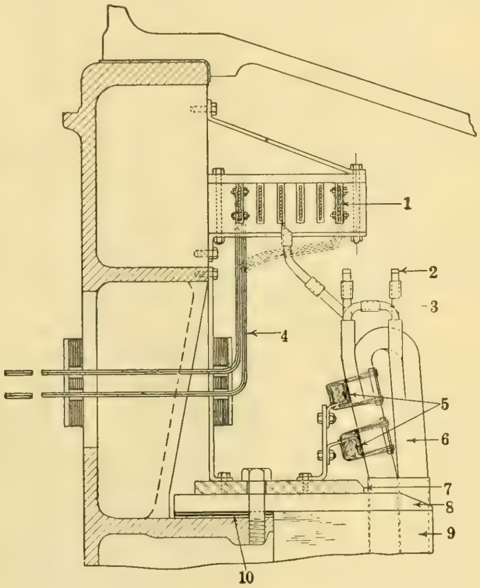
Where heavy windings project beyond the laminations, an additional support is provided by means of an insulated metal ring or brackets to which the outer ends of the coils are fastened, thereby protecting them from mechanical displacement or distortion due to magnetic disturbances caused by violent fluctuations or short circuits. This bracing is of greatest importance in large installations.

The windings are usually connected in Y, each end of each phase being brought out of the machine to permit the insertion of current transformers for protective relay equipments and for the grounding of the neutral, if desired.

With vertical generators, the cross-connections of the armature winding can be made on the upper side of the stator for convenience in connecting up the windings during installation and in making repairs; although if the leads are to be taken out at the bottom, they should, of course, be made there. For very large machines these phase-connections may be in the form of a bus-ring arrangement supported from the inside of the stator frame, see Fig. 201. The connections between these bus rings and the coils can be made with flexible connections which can readily be disconnected. Such an arrangement

allows free access to all the connections for cleaning and inspection, and permits the removal of damaged coils without disturbing the connections.

Medium- and large-sized generators, as well as high-voltage machines, should be provided with temperature coils located throughout the different parts of the armature winding, practical experience having demonstrated that when placed in the center of the core and in immediate contact between the coils, they will show the highest temperature. It is thus possible by means of suitable instruments, to determine the internal temperature of the windings with the machine in operation. According to the A.I.E.E. Rules, the insulation of the armature winding shall be such that it will withstand, for one minute continuously, a test voltage of twice the normal voltage plus 1000 volts. The frequency of the testing circuit shall not be less than the rated frequency of the generator.



1. Phase bus rings.
2. Pole connections.
3. Group connections.
4. Terminal leads.
5. Bracing rings.
6. Stator coil.
7. Clamping flange of core.
8. Clamping fingers.
9. Punchings or core.
10. Removable shims to allow taking up settling of core.

FIG. 201.—Arrangement of Stator Coil Connections and Coil Bracing Rings for Large Vertical Generators.

Field Spider. The rotating field generally consists of separate pole pieces mounted on a rotor, the design of which depends on the size, as well as the speed, of the unit. For moderate sizes and speeds, it often takes the form of a steel rim connected to the hub by means of arms of ample cross-section, like a flywheel. For high speeds and moderate capacities, it may consist of built-up sheet steel punchings; and for higher capacities with larger diameters, of rolled steel plates. Where shipping conditions permit, the field spider and the rim may be cast in one piece; otherwise it must be split into sections, either lengthwise or

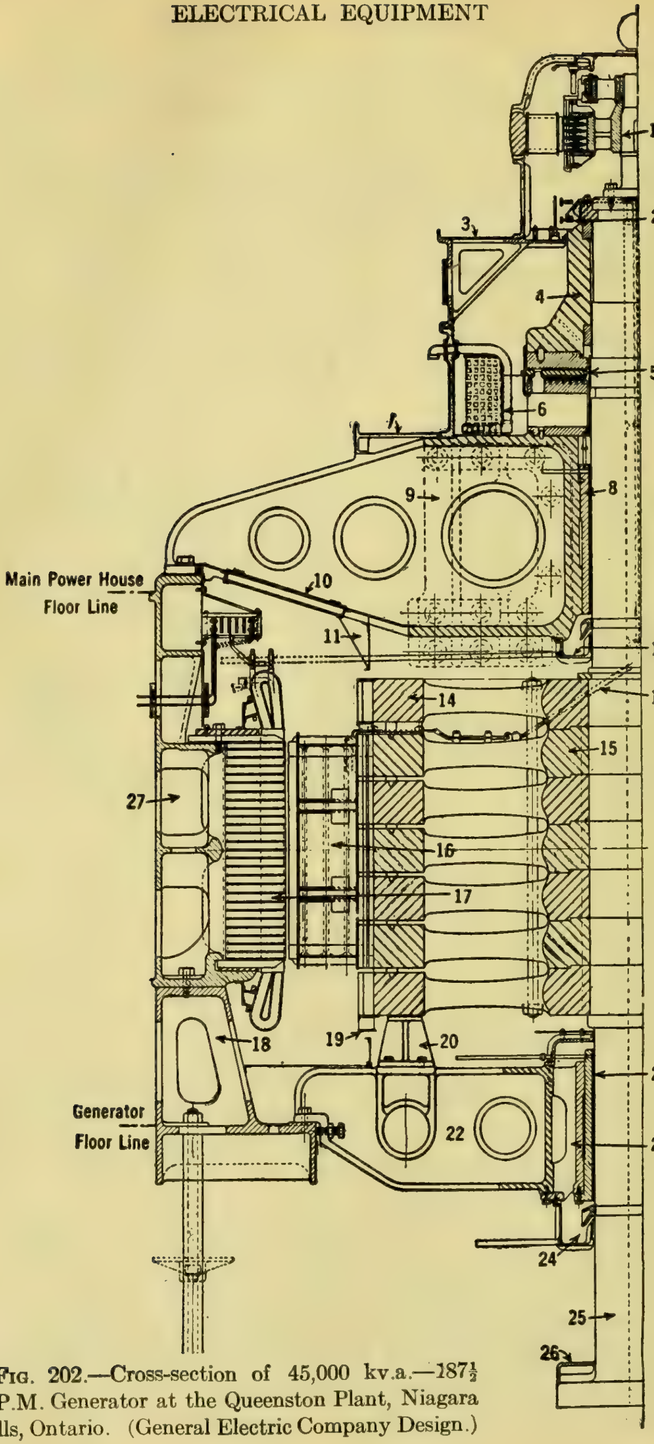


FIG. 202.—Cross-section of 45,000 kv.a.—187½ R.P.M. Generator at the Queenston Plant, Niagara Falls, Ontario. (General Electric Company Design.)

crosswise to the shaft. The former method is used when the diameter of the rotor is very great, and the latter method when the length is great. It is, of course, obvious that a rotor with solid rim is preferable to one containing joints; but, as stated, the diameter must be governed by transportation limitations. The sections should be securely held together by heavy bolts and link keys; and when the field is split crosswise to the shaft, one set of arms should preferably be provided for each section, so as to insure a rigid construction.

The rotor of the generator shown in Fig. 202 thus consists of no less than seven separate centers of flywheel construction, each wheel being made in one piece to insure maximum strength. The hubs of these wheels are rabbeted into each other and are slightly wider than the rims, so that openings are left between the rims to allow air to pass through the spaces between the pole pieces. The field coils are only attached to the fine center wheels, the upper and lower wheels merely being provided to give the required flywheel effect.

Field Poles. The pole pieces are built up of laminated sheet steel punchings, spreading at the pole face so as to secure not only a wide polar arc for the proper distribution for the magnetic flux, but also for holding the field coils in place. These punchings are either riveted or bolted together and reinforced by two stiff end plates. For machines of moderate speed the poles are simply bolted to the rim, while for machines of higher speeds they are solidly mounted on the spider by means of one or more parallel dovetail slots in the rim. These dovetailed grooves should be made somewhat larger than the corresponding part of the punchings, and a tight fit is obtained by means of steel wedges, which are guarded from falling out by bolted end rings.

The revolving parts of water-wheel-driven generators should be designed so as to keep the stresses due to centrifugal force, well below the elastic limit of all the material at the run-away speed of the water wheel. This speed varies with different types of wheels and different conditions of installation; but the general practice is to design the rotors with a 100 per cent overspeed in view.

Flywheel Effect. This problem should be considered when the design of the rotor is decided on, as well as when a comparison between different proposed generators is made. This is a hydraulic problem, and the turbine manufacturer specifies the WR^2 required to give the proper speed regulation. The amount specified is occasionally impractical, so far as the generator design is concerned; and with horizontal units it may be advantageous to provide a separate flywheel to take care of the additional flywheel effect above that provided by the generator rotor. For vertical units, however, such separate flywheels are

hardly practical, and the required effect must be provided for in the generator rotor, which then may mean larger diameters or increased weight, as was the case for the machine shown in Fig. 202, previously referred to. The following formula gives a rough approximation of the WR^3 required for generators driven by water wheels under normal conditions, or those corresponding to the usual characteristics of an average development.

$$WR^2 \text{ per kw.}_{(\max)} = \frac{c}{(\text{R.P.M.})^2}.$$

The value of the constant c should not be less than 4,000,000 for open flume construction, and may run as high as 10,000,000 or even higher for plants having long penstocks with reasonably high velocity.

In determining the available flywheel effect, consideration should also be given to other rotating synchronous apparatus on the system, which may represent a very large flywheel effect.

Field Winding. Two methods are used for winding the field coils; viz., the wire winding and the strip winding. For small machines, where even for moderate exciting voltages it is necessary to have many turns of small section, the cotton-covered wire-wound coil is usually selected. The necessary insulation may be placed on the assembled pole piece and the winding wound directly thereon. Heavy metal and fiber collars are provided at the ends, and serve to clamp the conductors together and prevent movement due to mechanical stresses.

The wire-wound field coil, however, has its limitations, both mechanically and electrically. As the centrifugal force of the field coil increases, the vertical component of the force will reach a critical value where the crushing stress on the cotton insulation around the individual wires becomes excessive, while at the same time the horizontal component tends to tear the wires from the pole. From the electrical standpoint the limitation is that of heating. It is evident that the heat generated in the inner layers of the winding can reach the outside surface of the winding only by passing through the insulation of each succeeding layer. This, of course, results in a very considerable difference in temperature between the inner and outer layers, and in order to operate the former at safe temperatures it is necessary to adapt comparatively low-current densities in the copper; this, in turn, results in a heavy winding and consequently high centrifugal forces.

In order to obviate these difficulties, inherent in the wire-wound field, it is customary to construct the winding of copper strip wound on edge. The method of insulating this type of winding is similar to that described for wire-wound coils, with the exception that the insu-

lation between turns consists of varnish, paper, asbestos, etc. It is evident that this type of coil will not only stand much greater vertical forces, but also, on account of the high moment of inertia of this flat strip, it is better able to resist the horizontal component of the centrifugal force. For higher speeds and with long field coils, supporting brackets are also necessary between the field coils, as shown in Fig. 203, to overcome the tendency toward lateral distortions and bulging out of the coil. Two or three such supports may be required for very large machines. Means should also be provided to thoroughly fasten the connections between the coils, and prevent them from being loosened by the strains imposed by the centrifugal force.

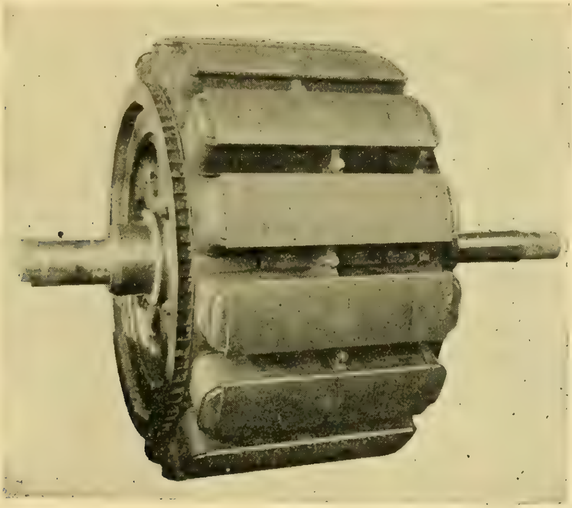


FIG. 203.—Rotor of Waterwheel-driven Generator.

The bare outside edge of the copper strip is exposed to the direct fanning action of the rotor; and since the temperature drop in the copper itself is negligible, that is, for the widths of strip ordinarily used, the heating of the coils is due almost entirely to surface drop. As a result, a higher current density can be used than would be permissible with the wire-wound field, and a higher " observable temperature " is permitted by the A.I.E.E. Rules, as previously mentioned.

The exciter current is conveyed to the revolving field through two collector rings mounted on the shaft of the machine.

According to the A.I.E.E. Rules, field windings for A.C. generators shall be tested with ten times the exciter voltage, but in no case with less than 1500 volts nor more than 3500 volts.

A rather unique design for a very high speed rotor is described in *General Electric Review* for February, 1920. This machine is rated 7000 kw. at a normal speed of 750 R.P.M., and the design is such that with a 100 per cent overspeed the stresses will not exceed one-half the elastic limit of any of the material. These considerations led to the use of the smallest diameter, consistent with other factors in the design, and the usual definite pole construction could not be used. Instead of a laminated pole keyed directly to the spider, the loose or removable tip construction was used to permit the rotor coils to be wound on a form and assembled separately or disassembled readily when making repairs. The rotor assembly is shown in Fig. 204, the rotor body and poles consisting of a series of steel plates machined to shape. Each plate is slotted across the pole face, at right angles to the shaft axis, to receive the pole tip, which is a separate steel bar machined to the shape of a pole tip as shown at *A* on the illustration. The plates are then bolted together in two sections, and these sections are again bolted together with through bolts, the whole forming the revolving rotor. The field coils, which are of the usual edgewise ribbon type, are mounted on the pole body, after which the pole tips are inserted in the slots in the pole body, as shown at *B*. Supporting brackets are placed between the coils and bolted directly to the pole body to prevent distortion of the coils.

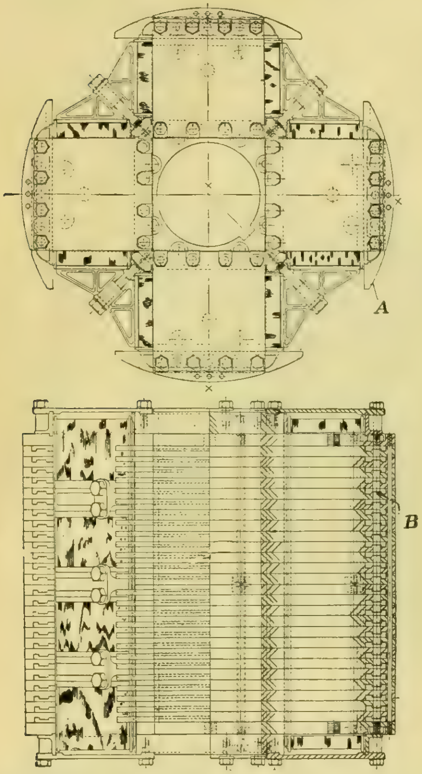


FIG. 204.—Rotor Assembly of 7000 kv.a., 750 R.P.M., 14,000 Volt Alternator.

Shaft. Shafts are, as a rule, furnished with water-wheel-driven generators and provided with forged coupling to be connected to the water-wheel shaft. Occasionally one single-piece shaft is used for mounting both the water-wheel runner and the generator field.

With horizontal machines, provision is often made for moving the

frame along the shaft for convenience in repairing the windings. With the construction shown in Fig. 205, this, of course, means an extra long and consequently larger and more expensive shaft, and in many cases the advantages are hardly worth the extra cost.

Bearings. The bearings of horizontal units are ordinarily of the self-aligning pedestal type, arranged for oil-ring lubrication. In large bearings, particularly for high-speed service, it often becomes necessary to provide artificial water cooling for carrying off the heat generated. Thin, coil-shaped copper pipe is imbedded in the lower bearing half, just below the surface of the babbitt and cooling water is forced through the coil. If the water wheel is of the overhung type, the size of the

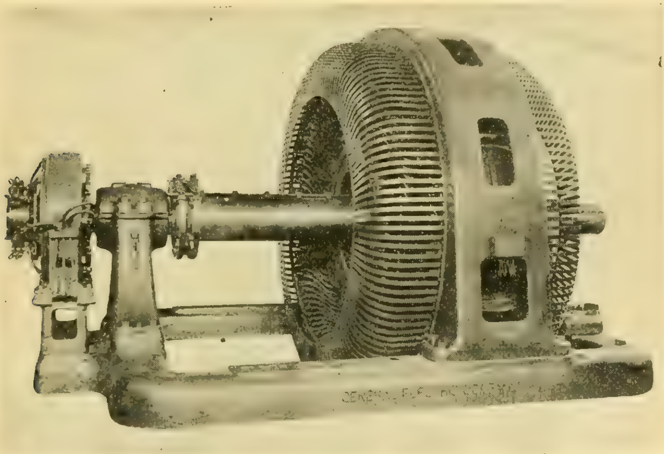


Fig. 205.—3500 kv.a., 500 R.P.M., 11,000 Volt Waterwheel-driven Generator of Open Construction.

bearing nearest the wheel must be of sufficient size to take care of the extra weight. Whether the water thrust is balanced or not must also be considered.

With vertical units, the present practice is to support the revolving element of the entire unit from a thrust bearing mounted on top of the generator frame. Two guide bearings are usually provided with the generators, one in the upper bracket directly below the thrust bearing, and the other one supported by a bracket below the revolving field (Fig. 206). Generally, one guide bearing is provided in connection with the water wheel. In case of very low-speed machines, where it is possible to use an exceptionally short draft, it is sometimes possible to omit the bearing immediately below the revolving field; but, in general, it seems preferable to have a bearing at this point. The thrust bearing

must sustain not only the weight of the revolving element but also the unbalanced water-thrust, and the top bracket must, therefore, be of

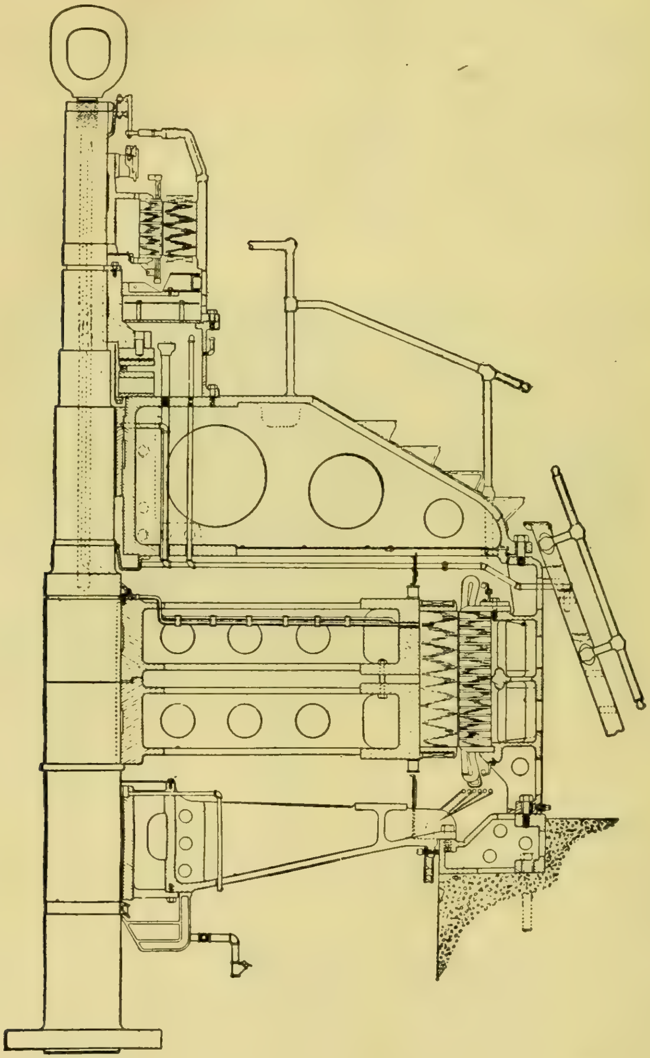


Fig. 206.—Sectional View of Modern Vertical Generator with Direct-connected Exciter, Moderate Speed.

adequate strength and is usually made of steel, heavily reinforced. Present designs generally follow a bridge construction with radial arms,

as seen in the various illustrations; and for large machines the bracket may be built in sections bolted together.

In order to obtain the proper clearance between the turbine runner and the casing, an adjustment between the upper bearing bracket and the stator frame can readily be provided.

The lower bearing bracket, in addition to supporting the lower guide bearing, may be designed to support the total rotating element when the thrust bearing is being dismantled. It is also used for supporting the brake equipment when such is used.

To avoid the possibility of circulating currents flowing through the shaft and bearings, one of the bearing pedals of horizontal machines,

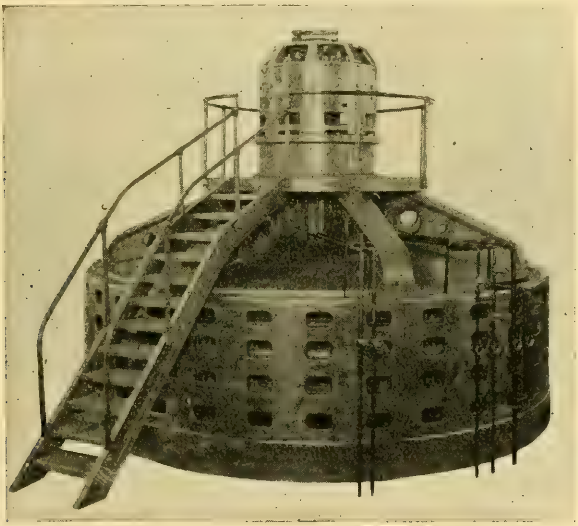


FIG. 207.—Vertical Waterwheel-driven Generator with Direct-connected Exciter.

and the upper bearing bracket of vertical units, should be insulated from the stator frame.

The collector rings are mounted above the thrust bearing, either below or above the direct-connected exciter, if such is used. See Figs. 202 and 206. A circular platform with guard rail facilitates inspection and adjustment, and access to it can be had by a ladder or walk directly from an adjacent gallery, as the case may be. See Figs. 207 and 218.

There are two types of thrust bearings generally used, the General Electric spring thrust bearing and the Kingsbury thrust bearing. The former, which is illustrated in Figs. 208 and 209, consists of a runner of a special grade of cast iron resting on a thin steel disc with a babbitted

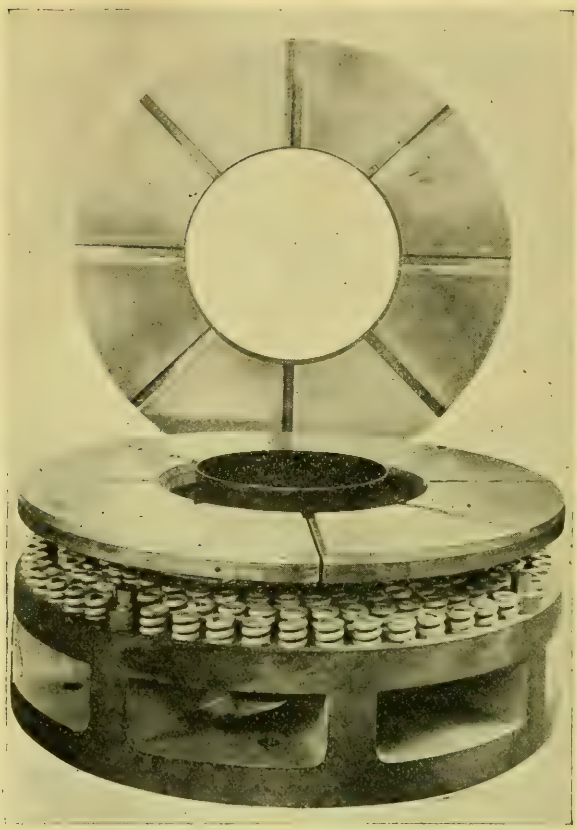


FIG. 208.—Spring-supported Thrust Bearing, Showing Rubbing Surface of Rotating Ring; Stationary Ring with Sawcut is Raised to Show Arrangement of Springs.

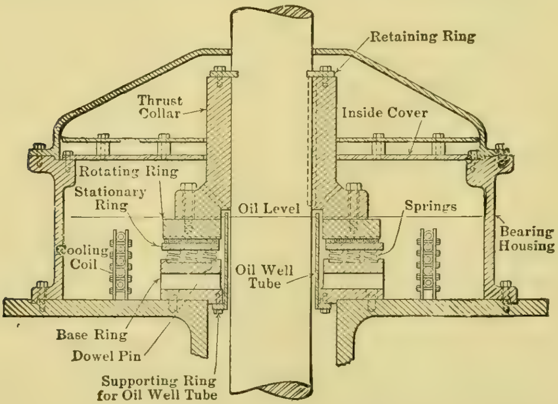


FIG. 209.—Cross-section through a Spring Thrust Bearing.

surface. This babbitted ring, in turn, rests on short helical springs and is held against rotation by dowel pins. The high base casting shown is used in connection with a deep housing in case it is desired to increase the amount of oil in the surrounding bath. The tube in the center forms a retaining wall around the shaft for the oil. The springs shown are wound of $\frac{1}{2}$-inch round wire and have an outside diameter of 2 inches and a free length of $1\frac{1}{2}$ inches. Under load, the springs close about $\frac{3}{32}$ inch, and the total pressure is distributed upon all of them. The cast-iron runner is located on the underside of the thrust collar, which is fastened to the top end of the shaft by means of a retaining ring. The bearing surface of this runner is finished with extreme accuracy and is given a high polish. The babbitt surface upon which this runner revolves has radial oil grooves cut in it, and it is cut entirely through in one of these grooves to prevent any tendency to dish or warp under changes in temperature.

With smaller water wheels, where the clearance between the runner and the stationary parts are small, it might be desirable to pre-compress the springs to a position corresponding to full load on the bearing; this is readily accomplished by the use of washers and clamping screws. With such a bearing, there is no further deflection of the springs as a whole while the weights of the generator and water wheel rotors are being placed on the thrust bearing. If, however, there are high local pressures on any part of the babbitt surface, the springs directly below will be further compressed, and the pressure on these spots will be relieved before it reaches a value that will cause "wiping" of the babbitt. Cooling coils, immersed in the oil in the bearing housing, and through which water is circulated, will abstract the heat from the oil surrounding the bearing and effect a considerable saving in the quantity of oil required and consequently also in the capacity and cost of the lubricating system. This is an advantage which can not be overestimated.

The spring-supported thrust bearing furnishes the runner with a flexible support which will automatically adjust itself, while in operation, to any tendency towards unequal distribution of the load, caused by inaccuracies in workmanship or alignment.

The Kingsbury thrust bearing, illustrated in Fig. 210, consists of a stationary and a revolving plate, submerged in a bath of oil under atmospheric pressure. The lower, stationary plate is divided into a number of babbitted segments spaced far enough apart to permit a free circulation of oil. Each segment, or shoe, has a single pivot support located toward one end of the shoe, slightly beyond the center of gravity in the direction of rotation. This arrangement causes the space be-

tween the shoe and the thrust block on the shaft to open slightly at the other end of the shoe, where the oil is drawn in by the rotation of the thrust block. The film of oil on the face of the shoe thus assumes the form of a very fine wedge constantly urged forward by the rotation of the thrust block.

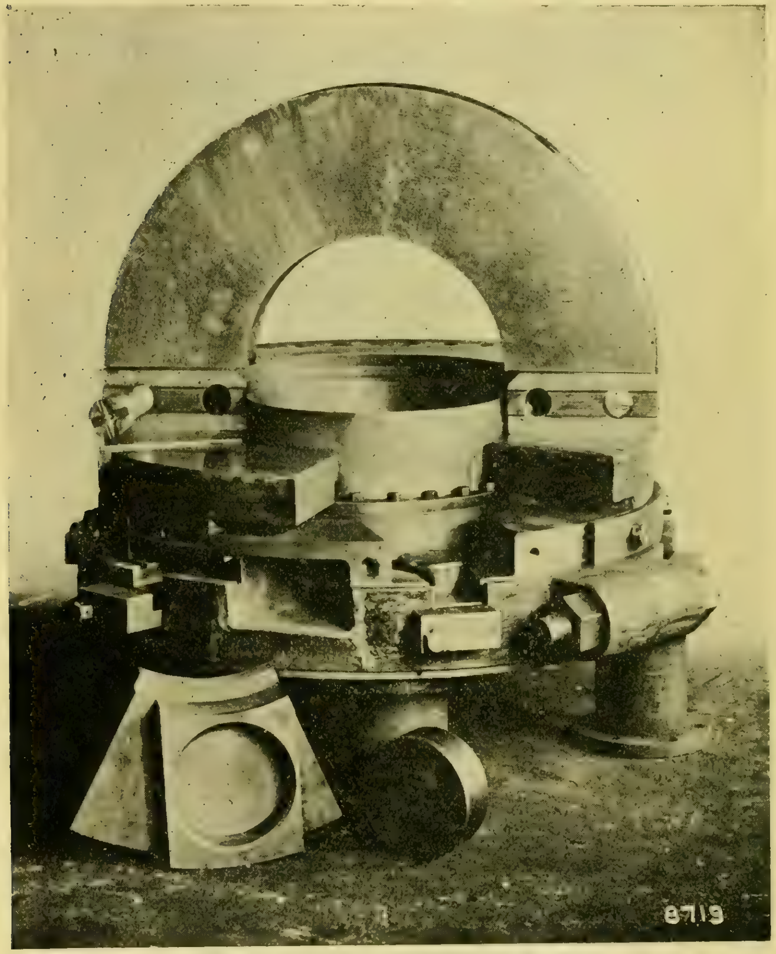


FIG. 210.—Kingsbury Thrust Bearing.

Lubrication. With horizontal generating units, self-oiled bearings are, as a rule, sufficient, and, in most cases no other oiling system is installed. In a few cases, connections are provided for draining the oil at intervals for purifying, and with large units this is desirable. Water

cooling is usually provided for in the bearings of large machines, as previously mentioned. The adoption of thrust bearings for large units has, however, presented a new engineering problem, that is, the proper

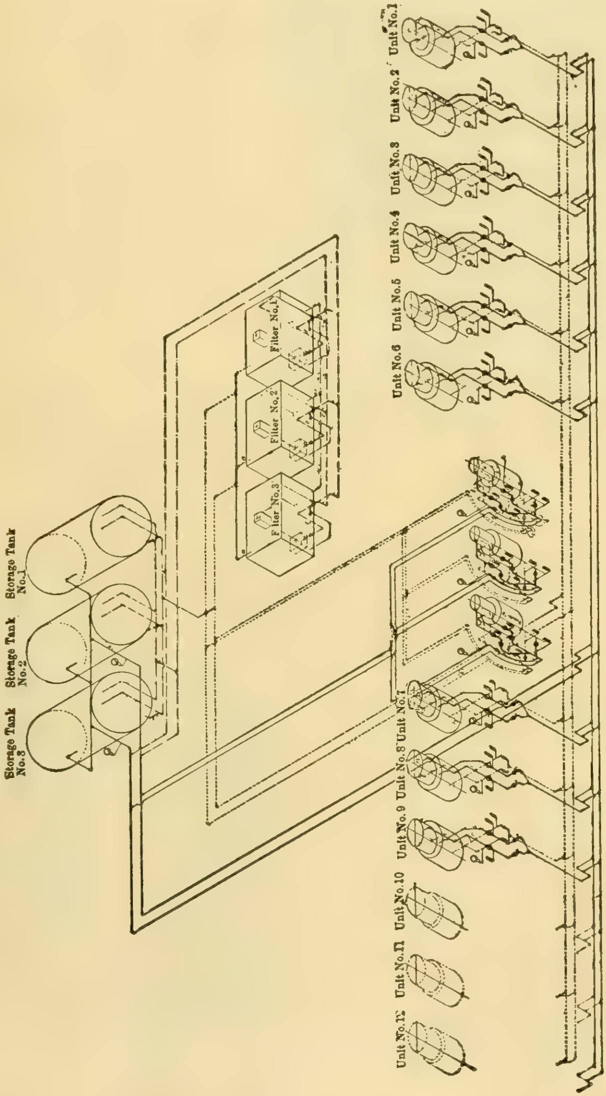


FIG. 211.—Oiling and Filtering System.

design of an oil-circulating and oil-purifying system, which will supply these bearings at all times with a sufficient quantity of cool, clean oil. With the two types of thrust bearings previously described, which

require only atmospheric oil pressure, the conditions are much simpler than with older installations where pressure bearings were used.

In general, there are two types of lubricating systems used, the centralized system and the individual system. The former is generally used for large installations, although individual lubrication is rapidly gaining headway even in these plants, owing to its much simpler piping arrangement and consequent lower cost.

With the centralized system, the oil supply may be of the gravity-feed or the pressure type. With the gravity type, as shown in Fig. 211, clean oil is stored in overhead reservoirs, and is then distributed to the thrust and guide bearings on each unit by means of a suitable system of piping. After passing through the thrust and guide bearings, the used oil flows by gravity to purifiers located in the basement, and is

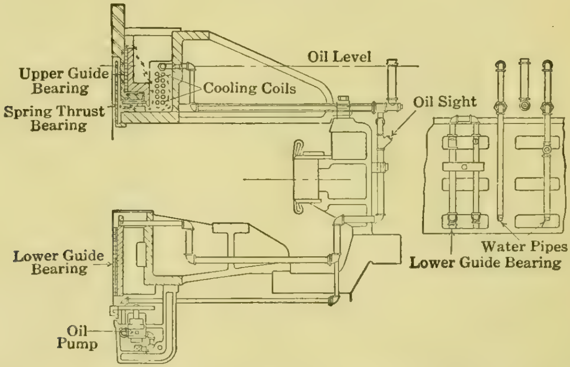


FIG. 212.—Arrangement of Oil and Water Pipes on Self-oiling Vertical-Shaft Generators Having a Combined Thrust and Upper Guide Bearing.

then returned by automatically controlled pumps to the overhead reservoirs ready for re-use. A great saving in the amount of oil can be effected as previously stated, by water-cooling the oil directly in the thrust bearing housing.

The oil may also be distributed to the generators by pump pressure, and the return oil passed into storage tanks by gravity. Important plants usually provide duplicate oil pumping equipments, and in certain instances also an emergency oil storage supply under air pressure, suitable for operating the plant for one hour.

Figures 212 and 213 show the General Electric system of self-oiling units. In this particular case, the upper guide bearing is above the thrust bearing and runs in the same oil bath, radial grooves in the thrust bearing pumping the oil from the thrust bearing through the upper guide bearing. The oil for the lower guide bearing is generally

first pumped up to a convenient height, where the operator can regulate and observe the flow to this bearing. An oil pump is located in the drain pan of the lower guide bearing, and circulates the oil for this bearing. The pump is geared to the generator shaft and is mounted so that one-half of the oil pan may be removed without disturbing either the pump or the discharge pipe. The oil is removed occasionally and the housings refilled with new or purified oil.

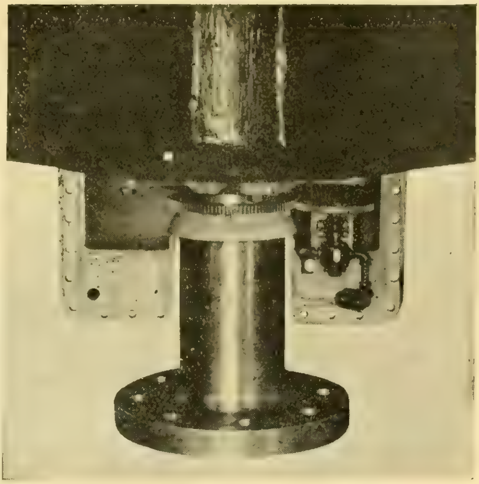


FIG. 213.—Individual Direct-geared Oil Pump in Oil Pan on Lower Guide Bearing of Vertical Generator.

For larger generators with the upper guide bearing below the thrust bearing the pump in the lower drain pipe will pump the oil to the thrust bearing housing, whence it flows by gravity to the guide bearings; and the returns from all the bearings may be taken to an oil purifier located below the generator or at any convenient point near the unit.

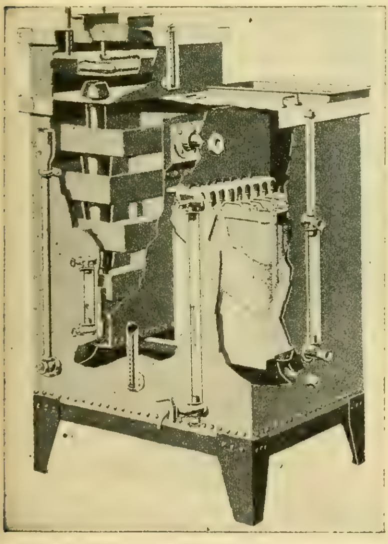


FIG. 214.—Cross-section of Richardson-Phoenix Power Plant Oil Filter.

There are two general classes of oil purifiers, the gravity or precipitation type and the centrifugal type. Of the former, the Richardson-Phoenix make, shown in Fig. 214, is most widely known. In this type, the oil enters through a strainer box and passes through a series of trays, where any water is separated in order that it may not again come in contact with the traveling oil. The partly purified oil then flows into the filtering compartment, which contains a number of filtering units. Each of these units consists of a galvanized wire screen held in a metal frame, the whole

being covered by a cloth bag. The oil passes from the outside to the inside of the filtering units, then through nozzles which project through the wall of the filtering compartment, to the clean oil compartment. Any individual unit can be withdrawn without interfering with the continuous operation of the filter. The pump for circulating the oil may be geared to the main unit, as previously described for individ-

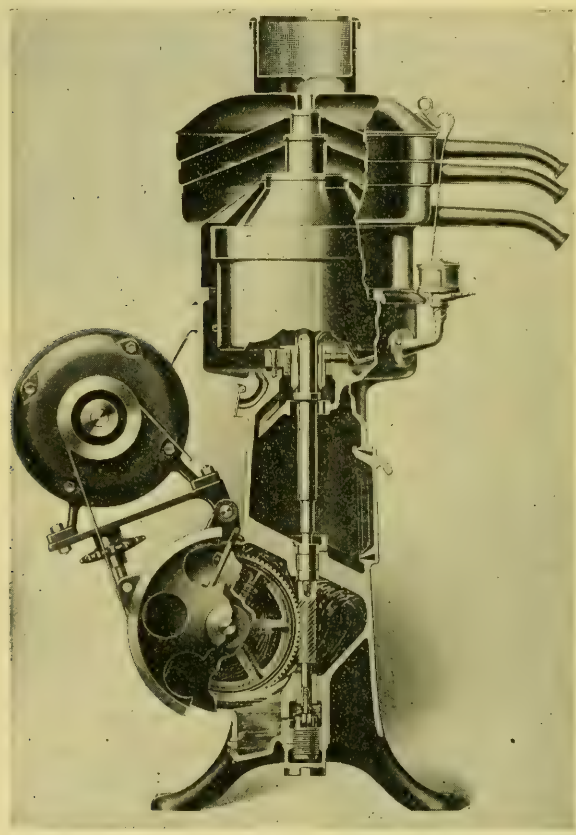


Fig. 215.—Cross-section of Motor-driven De Laval Centrifugal Oil Purifier.

ual oiling systems, or it may be located near the filter, or at any other convenient point.

The centrifugal oil purifier works on the long-known principle that, with the proper application of centrifugal force, liquids of different specific gravities are instantly separated and solid impurities removed from them.

Figure 215 shows a cross-section of a De Laval motor-driven centrif-

ugal oil purifier. The purification takes place in a revolving bowl at the top containing a series of discs which divide the liquid into thin sheets or layers and thus greatly increase the rapidity and effectiveness of the purification, and still make it possible to run the bowl at a comparatively low speed.

Surmounting the bowl are three covers, having spouts from which the various liquids are discharged. These covers serve the following purposes. The water discharged from the bowl is collected in the lower cover and emptied through the spout leading from it. The purified oil is collected in the second cover and is discharged through that spout. The top cover, known as the overflow cover, is provided in order that if at any time the bowl becomes clogged by a large amount of dirt, so that the liquid can no longer flow through, the inlet tube will fill up and overflow into this cover. This keeps the overflow separate and acts as a warning signal that the bowl needs cleaning. At the top is the regulating cover into which the liquid to be treated flows before it passes into the bowl.

The oil piping, as previously stated, becomes very much simpler with the individual oiling system than with the centralized system, where it may be quite complicated and costly. Such piping should be laid out carefully to permit of readily draining and cleaning the pipes, and air pockets should be avoided. Return drain should be amply large and properly pitched to rapidly and thoroughly remove used oil. It is better to err on the safe side and have the returns a size or two too large, rather than to have them too small with consequent flooding of machines and wastage of oil. All feed pipes should be of brass or reamed steel pipes. All joints should be carefully reamed and the piping blown out with steam or compressed air as they are installed. Arrangement for a temporary connection from the feed pipes to the return drains at the machines is advisable. This allows of thoroughly flushing out all dirt by kerosene or oil before any oil is fed to the bearings. The piping should be equipped with valves and unions to permit readily disconnecting a machine for repair work. All bearings should be equipped with sight feeds or some similar arrangement to show when the oil is feeding profusely. This should preferably be in the return, as this indicates that oil is actually going through the bearings. Thermometers are also often provided with large units for reading the temperature of the thrust bearing.

While there are many modifications of the systems described above, they will serve to indicate the general types of oiling and filtering systems now in vogue. The design of these oiling systems is a highly specialized branch of engineering, because in laying them out and

determining the pipe sizes it is necessary to take into consideration the kind of oil to be used, and especially its viscosity, the flow of oil being dependent upon the viscosity, which, in turn, varies with the temperature of the plant. These factors all have to be considered in laying out the piping, calculating the quantity of filtering surface, and designing the pumps.

Ventilation. The problem of generator ventilation is of the greatest importance for a successful operation. The quantity of cooling air required is approximately proportional to the losses, and for small machines the problem becomes quite simple. These may therefore be of entirely open construction (Fig. 205), the radiating surfaces combined with the natural draft set up by the revolving field being generally sufficient to carry away the heat generated in the machine. The

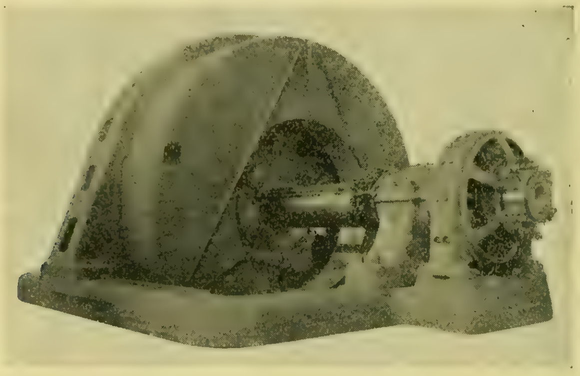


Fig. 216.—Horizontal Waterwheel-driven Generator of Semi-enclosed Construction.

ventilating ducts in the stator core and the holes in the frame and in the rotor rim between the pole pieces are of great assistance in distributing the air properly. Baffles are also placed between poles in some cases to stop air from passing axially between the rotor poles, resulting in a more even distribution through the stator.

Medium-sized machines may have the rotor equipped with fans at both ends to assist in forcing the air through the machine (Fig. 203). Horizontal units can then be provided with sheet-iron enclosing shields, the air for ventilation being drawn into the machine around the shaft by the action of the fans and the revolving field, and then expelled into the room through openings in the stator frame (Fig. 216). By means of the enclosing end shields, a definite path for the air is provided, the fans forcing the air into these shields where it will be put under a certain pressure, thus insuring an effective ventilation of the end windings.

The frame is provided with ventilating holes only above the base line, no outlets being provided toward the pit; and the air that passes through the core and windings below the base is forced out of the large openings in the feet of the armature frame. This will prevent the collection of heated air in the pit.

The usual method of ventilating small- and medium-sized vertical generators is to take the air from the bottom and top of the rotor and exhaust it through the stator into the station; or it may be taken entirely from the pit below the machine, in which case the top of the generator must be closed.

With almost all large generators, it becomes necessary either to pipe

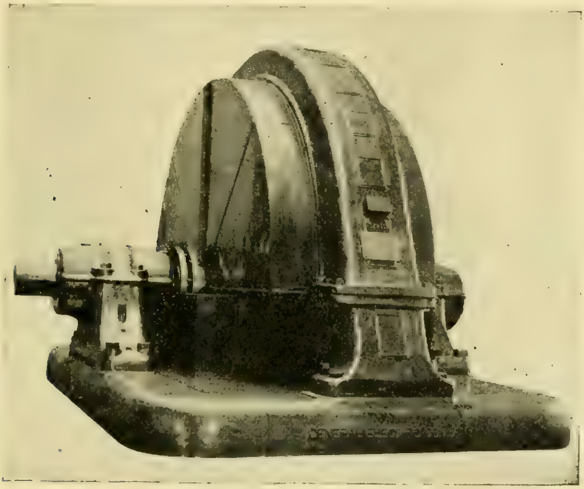


FIG. 217.—Horizontal Waterwheel-driven Generator of Totally Enclosed Construction.

the air to the machine or away from it or both. Figure 217, for example, shows a totally enclosed horizontal machine, the ventilating air coming in from the outside through ducts in the foundation, and being drawn into the rotor at each side. After passing through the machine, it leaves through a duct located at the bottom of the stator frame and is again discharged outside of the building. The holes in the stator frame are closed by covers which can be easily detached, if desired, to allow the warm air to escape into the station during the cold season, for heating purposes.

In addition to obtaining a definite flow of cooling air through the machine, the enclosing covers also reduce to a minimum the noise occasioned by the revolving parts.

This method of ventilation is also readily adapted to vertical units. In the installation shown in Fig. 218, the generators are of identical construction to that shown in Fig. 207, sheet-iron casings being provided around the stator frame. The air enters through the waterwheel pit, is drawn through the machine by its fan action and discharged through the holes in the stator frame into the casing and through ducts to the outside. In this case the tops of the generators are enclosed, but these

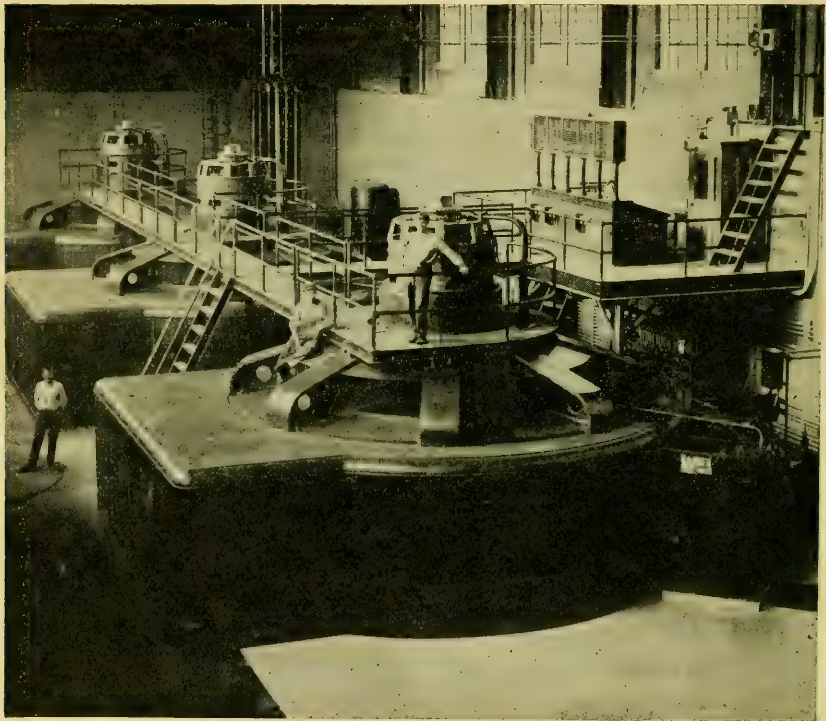


FIG. 218.—Three 18,000 kv.a., 154 R.P.M., 13,200 Volt Waterwheel-driven Generators at Tallassee Power Company, Badin, N. C.; Showing Enclosing Casings for Ventilation.

may be open in case it should be desired to take the air from the generator room as well as from the wheel pit.

Doors or covers may, of course, be provided in the casing or in the exhaust ducts, so that warm air can be admitted for heating the station in cold weather, as explained above. It may also be used to heat the ice runs.

A reference to Fig. 85 on page 148 will show the interesting arrange-

ment of the large generators at the Queenston plant of the Ontario Power Co. The enclosing feature is obtained by locating the generator room floor at the same level as the top of the generator frame. The spaces between the arms of the upper bearing bracket are enclosed, as is the space between the stator frame and the adjacent generator room floor. Cooling air is admitted to the pit beneath the generator through ducts from the outside of the stations, or from the generator room, or from both, and is drawn into the machine by the blower action of the rotor. It is expelled through the openings in the stator frame into a chamber surrounding the generator, and is then exhausted by a fan through a ventilating shaft through the roof, or to different parts of the building for heating purposes.

High-speed generators with fans mounted on the field spider are, as a rule, self-ventilating. With large, slow-speed machines, however, the peripheral speed of the rotor may be insufficient to produce the required air pressure for their proper ventilation, even if ventilating vanes are provided on the rotor. In such cases, independent motor-driven fans must be provided.

The quantity of air required for cooling a generator depends on several factors in the design; but in general it varies approximately with the losses. Experience has also shown that an approximate figure for the amount of cooling air required is 100 cubic feet per minute for each kw. loss. This will cause a temperature rise of the air passing through the generator of 18° C., and if this is not exceeded there should be no danger of the generator attaining a temperature in excess of the permissible value. Should the temperature rise of the cooling air greatly exceed the value given above, it would indicate that the air did not effectively carry away the heat, and the air supply should then be increased.

The design of the air ducts should be very carefully studied in order to reduce their resistance to a minimum. This resistance is dependent on the change in direction and cross-section, on the condition of the surface of the ducts, and on the superficial area of the duct per unit length. It is necessary to take into account the fact that for the same area of cross-section a round or square section has less friction than a rectangular section. Unless the deviation is great, it may, however, be neglected. The ducts should, therefore, be of ample cross-section, as short as possible, and without sharp bends.

The air moving in a duct exerts a certain pressure (impact head) on a plane at right angles to its path, and a different pressure (static head) on a plane parallel to its path. The difference between the two is the pressure (velocity head) due to the velocity of the air. If the

duct is uniform in cross-section, the velocity of the air and the velocity head do not change, but the impact head and the static head decrease by the same amount in the direction of the flow of air, owing to the friction of the sides of the duct and to the friction of the eddy currents in the air. The pressure of air is usually measured in inches of water, but can readily be converted into other units, as follows:

TABLE OF CONVERSIONS

	Inches Water Pressure.	Inches Mercury.	Ounces per Square Inch.	Pounds per Square Inch.	Pounds per Square Foot.
1-inch water pressure...	1.00	0.0736	0.577	0.036	5.19
1-inch mercury pressure	13.6	1.00	7.84	0.49	70.6
1 ounce per square inch.	1.73	0.127	1.00	0.0625	9.0
1 pound per square inch.	27.7	2.04	16.00	1.00	144.0
1 pound per square foot.	0.192	0.0142	0.111	0.00694	1.00

If V = Velocity of air in feet per minute;
H_v = Velocity head in inches of water.
Then

$$H_v = \left(\frac{V}{4000}\right)^2.$$

Since the drop in pressure of air passing along a duct is dependent on the velocity of the air, it is convenient to consider this drop in terms of H_v (velocity head); and the following equation, based on experience, may be used for determining the loss of static head in a concrete duct of round or square cross-section:

$$H = \frac{H_v L}{26h},$$

where H = Loss of static head, in inches of water, due to friction;
L = Length of duct in feet;
h = diameter of duct (i.e., diameter of round duct or side of square duct).

Experiments have also shown that a right-angle turn, with an outside radius equal to the diameter, results in a loss of static head equal to the velocity head. The loss due to abrupt reductions in the area is also equal to the velocity head in the duct.

The loss in static head, or the difference in pressure necessary to

force air through a round or square concrete duct, can therefore be approximately calculated from the following equation:

$$H=\left(a+b+\frac{c}{26}\right)H_v,$$

where H_v = Velocity of head;
a = Number of right-angled turns;
b = Number of abrupt reductions in area;
c = Length of duct ÷ diameter of duct.

The proper velocity of the air in the ducts should be a function of the peripheral speed of the generator rotor. For example, with low-speed machines having a peripheral speed of around 6000 feet per minute, an air velocity of 600 feet per minute in the air passages should give good results, while with high-speed machines with a peripheral speed around 15,000 feet per minute the air velocity in the ducts may be about 1200 feet per minute.

Assuming a duct with 3 right-angle turns, 2 abrupt reductions in size, and 20 diameters long, the pressure necessary to force air through it at a velocity of 1000 feet per minute would thus be:

$$H_v=\left(\frac{1000}{4000}\right)^2=0.063$$

and

$$H=\left(3+2+\frac{20}{26}\right)0.063=0.35 \text{ inch.}$$

The resistance of the air passages through the generator itself is always considerably higher than that of the ducts. The fan action of the generator rotor will, however, generally create a sufficient pressure to overcome this resistance, unless the speed should be very low. With short, straight ducts, the pressure created may also be sufficient to force the air through the ducts. It is a very difficult problem to predetermine the resistance offered by the air passages of the generator, and experience from previous machines is as a rule generally relied upon for this.

The static pressure created by curved-blade generator fans can be approximated from the following formula:

$$H_f=\frac{1}{3}\left(\frac{V}{4000}\right)^2,$$

where H_f = Static pressure of fan in inches of water;
V = Peripheral velocity of fan in feet per minute.

The constant $\frac{1}{3}$ takes care of the losses and is based on the result of average practice.

Brakes. Water-wheel-driven generators should preferably be provided with brakes for bringing the machine to rest and for holding it in case of leakage through the wheel. They are of value in case of accidents, when it becomes of greatest importance to stop the unit in the shortest possible time.

For horizontal units and for small vertical machines, the brakes may be in the form of a hand brake acting on a flanged pulley attached to the shaft. The usual practice for vertical machines is, however, to apply the brakes to the generator rotor, the brake shoes, which are made of a special asbestos material, bearing directly against the lower side of the field rim. They are then mounted on the lower guide bearing bracket, and air pressure is used for their operation. They are generally designed so that they will bring the unit to a standstill in five minutes or less with a gate leakage of 5 per cent.

The brakes should be of rugged design, as they may be called upon to support the whole weight of the rotating element in case of repairs to the thrust bearing. They may even be used for jacking up the rotor to relieve the weight on the thrust bearing for such purposes, in which case the required pressure may be obtained by a hydraulic hand-operated oil pump.

3. INDUCTION GENERATORS

Output and Excitation. The induction generator is simply an induction motor driven above its synchronous speed. It requires a wattless exciting current for its operation and can, therefore, not be operated as a self-contained unit, but only in connection with synchronous machines, generators or motors. These machines will then furnish the necessary excitation, and also entirely govern the voltage and frequency of the induction generator.

The output depends on its speed above synchronism, and, with the speed of the induction generator constant, it can only be increased by decreasing the speed and thus the frequency of the synchronous machinery. There can be no permanent short-circuit current flowing, inasmuch as the exciting current disappears when a short circuit takes place, and the momentary current rush is also very small.

Comparative Capacity of Induction and Synchronous Generators. Inasmuch as the induction generator cannot furnish any wattless exciting current for the inductive load on the system or for its own excitation, it follows that this must be furnished entirely by the synchronous machines, thus necessitating an increase in their capacity. For example,

assume that a system carries a load of 8000 kw. 0.80 P.F., and that it is desired to install an induction generator having a capacity of 4000 kw. 0.95 P.F. What would the required capacity of the synchronous generators then be?

The wattless components of the load and the induction generator, which the synchronous generators must supply will be 6000 kv.a. and 1315 kv.a., respectively; and, as in addition they must furnish the remaining energy of 4000 kw. their capacity would have to be

$$\text{kv.a.} = \sqrt{4000^2 + 7315^2} = 8300$$

or twice that of the induction generator, and the power factor would be very low. A somewhat larger generator could, therefore, carry the entire load without any induction generator.

For a higher power factor, however, the condition would be different. If the power factor of the load, for example, were 0.95 instead of 0.80, the total wattless kv.a. to be supplied would only be 2635+1315=3950 and the capacity of the synchronous generators.

$$\text{kv.a.} = \sqrt{4000^2 + 3950^2} = 5600.$$

For low power factors it is, therefore, not very advantageous to use induction generators.

Operation. When putting an induction generator into operation it is only necessary to bring it up to speed and close the switch. Synchronizing is not needed, inasmuch as the machine cannot generate any E.M.F. until excited from the line; and when so excited it will, of course be in phase.

The first current rush is only exciting current, because the load cannot be picked up until the field is established. If the current rush should be undesirably large it can readily be reduced by inserting reactances when the machine is thrown on the circuit. These coils can then be cut out as soon as a steady condition is reached.

When driven by governor-controlled water wheels, the speed of the induction generator will drop slightly with the load, and in order to divide the load properly it will be necessary for the speed of the synchronous generators to drop still more. The best method of operating induction generators is, therefore, to drive them with wheels without governor control. In this manner their output will be kept constant and the load fluctuations will be taken care of by the synchronous generators.

4. EXCITERS

One of the problems in connection with large generating stations which should be very carefully considered is that of excitation. Upon it depends, to a large extent, the successful operation of the plant. The capacity of the exciter units, the proper division of the required exciter capacity into several units, the method of drive, whether by separate prime movers, by individual motors, or whether direct-connected to the main generating units, the arrangements and connections of the different units, the proper system of automatic voltage regulation, etc., are all factors which demand a careful consideration when a power plant is designed.

Separate Excitation. All synchronous machines are now separately excited, the excitation being obtained from some direct-current supply source. Generally, separate direct-current generators are provided for this purpose, and when so utilized are termed "exciters."

A separately excited generator has no inherent tendency toward regulation, this being effected either by a rheostat in the field circuit or by means of different systems of automatic voltage regulation, as discussed more fully in the next section.

Capacity and Rating. The exciters should have a capacity sufficient to excite all of the synchronous apparatus in the station when these machines are operating at their maximum load and at the true operating power factor. It is not enough to provide for the excitation when operating at unity power factor, because the excitation which is required at lower power factors is considerably higher than at unity power factor. It is considered good practice to make the combined capacity of all the exciters equal to the excitation required for all the generators, when these are operating at their maximum load and stated power factor (usually 80 per cent), plus a 20 per cent addition for possible variations in the required excitation.

Auxiliary station apparatus should not be operated from the exciter system, since troubles are always likely to occur in these circuits, and the exciters may thus be damaged at times when such damage would cause considerable inconvenience in the operation of the station. In most stations, station auxiliaries are now entirely operated by alternating current, and the direct current for the control circuits can be easily taken care of by the use of a small motor-generator set combined with a storage battery. No complications are then introduced by voltage fluctuations caused by automatic voltage regulators. Reserve capacity in case of breakdowns should, of course, be provided, the amount depending on the number of units.

Exciters are now given a maximum continuous kw. rating based on a temperature rise not exceeding 50° C., as measured by thermometer, above an ambient room temperature of 40° C.

Voltage. The pressure most commonly used for excitation is 125 volts. For A.C. machines of very large capacity requiring a large excitation, it will, however, usually be found more economical to use a 250-volt excitation. This higher voltage will permit the use of smaller exciter and field switches, while leads of reduced size from the exciters to the busbars and from the busbars to the generator field may be used, and the cross-section of the busbars cut in two; all this is of importance in reducing the cost, especially in large installations. A considerable saving can also generally be accomplished in the exciter itself. Machines for 125 volts require a commutator twice as large as those for 250 volts; and with water-wheel-driven units, where they must be designed to safely withstand double speed, the construction oftentimes involves considerable difficulties and expense.

Characteristics. When exciters are to be operated in connection with automatic voltage regulators, as is almost always the case, it is most important that they be designed with this point in view. The densities, especially in the fields, should be fairly low, as with high density the time element required to vary the voltage from one point to another would be so long as to materially affect the regulation. The greater part of the operating range should, therefore, be below the bend of the saturation curve.

The time element should be such that the exciter will be just sufficiently responsive to changes in the field excitation; that is, when an external resistance equal to about three times the resistance of the field, is inserted, the voltage should fall from 125 to 25 volts in from six to eight seconds. An ideal exciter designed along these lines should also give at full field at least 165 volts, and the increase in the field current from 125 volts to 150 volts should not be over 50 to 75 per cent depending on the exciter capacity.

For alternators operating at maximum inductive load, 125 volts is generally required for the excitation; and in order to get a satisfactory regulation when an automatic regulator is used, the exciter must be designed so as to be able to give 165 volts momentarily. It is also necessary that the increase in the exciter field current should be small, so that the exciter will respond quickly to the short-circuiting of the rheostat, and thus insure the desired alternator excitation. With generators feeding long distance transmission lines, or with synchronous condensers, where it may be required to operate from full capacity power factor lagging to full capacity

power factor leading, exciters with extreme voltage limits may be required.

Should the excitation voltage be any other value than 125, viz., 250 volts, the above values would be proportionally changed. (See also under Synchronous Generators.)

Shunt vs. Compound Wound. While an exciter may be either compound wound or shunt wound, the former is considered preferable for parallel operation with automatic voltage regulation.

Non-regulating exciters should be more or less highly saturated in order to insure a stable parallel operation. If such exciters were to be used with automatic regulation, they would be rather slow to correspond to the changes in field excitation. If a shunt-wound exciter is designed for a low saturation, so as to make it a good regulating exciter, it may have a tendency to unstable operation when running in parallel without a regulator.

Most exciters are of the commutating-pole type, and in order to

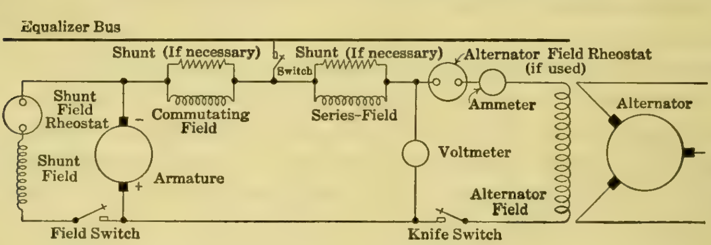


FIG. 219.—Elementary Diagram of Exciter Connections.

insure a successful parallel operation with proper division of load, they must have a drooping voltage characteristic, the compound-wound type without the series winding. The commutating field should be proportioned so that the machine is not over-compensated, because over-compensation would tend to magnetize the main pole and therefore, would have a compounding effect, the magnetizing effect being due to the short-circuit current in the coil undergoing commutation. The design should also be such that some range of brush shifting is allowable, and the brushes should be given a slight forward shift so as to obtain a drooping characteristic at all voltages within the range where parallel operation is required. With this arrangement, exciters, when compound wound, may be compounded flat at 125 volts and still operate properly in parallel at lower voltages.

The series field excitation of regulating exciters should not exceed 30 per cent of the total excitation, and the resistance of the rheostat

should be about three times that of the resistance of the exciter shunt field when hot.

For regulating exciters, which are not to be operated in parallel, the shunt-wound type is entirely satisfactory, provided it has been designed with this point in view, that is, for low saturation.

In Fig. 219 is given an elementary diagram of exciter connections. Sometimes German silver strip shunts are provided for adjustment across the series or commutating pole fields, but on most exciters the required compounding is obtained by shifting the brushes forward, provided it does not disturb a good commutation. This has also, as stated, the additional advantage of insuring a drooping voltage

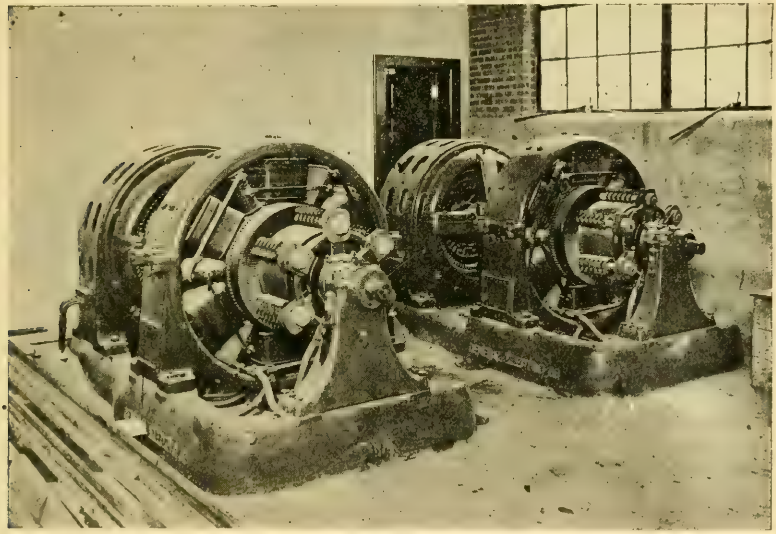


FIG. 220.—Induction Motor-driven Exciters.

characteristic at lower voltages, which is necessary for successful parallel operation.

Speed. The speed of an exciter depends on the method of its drive and on its capacity. Extremely slow or high speeds mean excessive cost, with the addition of mechanical difficulties for high speed. This is especially important in hydro-electric installations, where the exciters are turbine driven, in which case they must be designed to withstand the increased stresses due to a double-speed. This fact should not be neglected when making a decision on the speed of a water-wheel-driven exciter.

Method of Drive. While the exciters can be either belt-driven or direct-connected to the machines driving them, the latter practice is

almost exclusively used except in the very smallest plants. The direct connection may be either to the main generators, to separate water wheels or to motors, usually of the induction type. Sometimes, although rarely, an exciter may be found that is connected both to a motor and a turbine, the latter running idle when the motor is carrying the load, and vice versa.

Mechanical Design. The mechanical design of exciters does not differ from other direct-current generators. They may be either of the horizontal or vertical type, the latter construction being used for units direct-connected to vertical main generators or directly to vertical water wheels. When intended for direct connection to horizontal

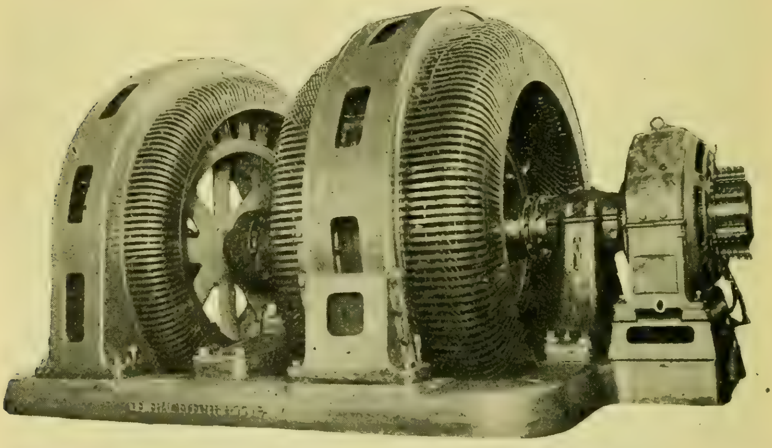


FIG. 221.—3000-kw. Frequency Changer Set, Showing Mounting of Direct-connected Exciter.

water wheels, they are almost invariably of the pedestal-bearing type, the shaft being provided with the necessary coupling. Care should be taken in designing the bearings to see that the water thrust, if any, is provided for. The same construction is also generally used for large motor-driven sets, Fig. 220, the two units being mounted on a common base. Occasionally only two bearings are used, with a common shaft. For horizontal units direct-connected to the main units, shaft and bearings are generally omitted, the exciter armature being mounted on an extension to the generator shaft and the frame supported on an extension to the generator subbase, as shown in Fig. 221.

Vertical direct-driven exciters, Fig. 222, are ordinarily provided with one or two guide bearings and a short shaft with coupling. The rotating element is supported by means of a thrust bearing located on

the upper bearing bracket. It should be of sufficient size to take care not only of the weight of the exciter armature, but also of the revolving element and water thrust of the turbine.

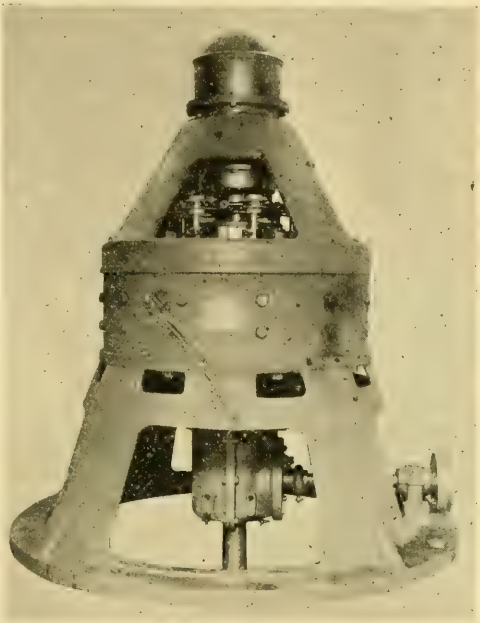


FIG. 222.—Vertical Water-wheel-driven Exciter, Showing Thrust Bearing at Top.

In the case of a vertical generator, the direct-connected exciter is usually carried by the thrust-bearing bracket, as shown in several illustrations in the section on A.C. generators.

Arrangements and Connections.[1] The choice of the proper exciter system is of utmost importance and should be given very careful attention. Exciter systems may be divided in two groups, the common or central system and the individual system, the exciters in either case being separately driven or direct-connected to the main A.C. generators.

In the common system, the exciters are operated in parallel on a common bus, from which the fields of the main generators are excited, a rheostat being inserted in each main field circuit. For large important installations, two sets of buses are sometimes provided, to secure increased flexibility and reserve capacity.

When separately driven, this system may employ either a turbine or motor, or both. Two exciters is the minimum which should be installed, and each of them should have a capacity to take care of the entire excitation of the plant, thus providing a 100 per cent reserve capacity. One of these can be water-wheel driven and the other motor driven, the motor being supplied with power from the main A.C. bus through step-down transformers, if necessary. For large stations it may be necessary to have three units, two of which, combined, can take care of the entire excitation, the third unit being held in reserve. This spare unit may be motor driven, although it is evident that two motor-

[1] See also Voltage Regulation.

driven units with a spare turbine-driven unit would cost less. This latter exciter would then also be used in starting up.

Water-wheel-driven exciters are, of course, not affected by the load and speed fluctuations of the A.C. system, but, on the other hand, such small turbines may readily become clogged up by debris and ice. An objection to motor-driven sets, which is occasionally raised, is that they are liable to drop out of step when a short circuit occurs on the system. This is, however, not the case with well-designed sets under momentary short circuits, and where it has occurred, it has been prevented by equipping the sets with flywheels. This, of course, increases the expense of the sets and is, as a rule, not justified.

Exciters direct connected to the main A.C. generators are also extensively used in the case of common excitation systems, especially where a small or moderate number of units are involved. This is a very reliable and efficient arrangement. Such exciters are, of course, affected by the speed fluctuations of the main units, and at runaway speeds they may cause over-voltages amounting to two or three times the normal voltage. Such over-voltages must, therefore, be guarded against by means of high-voltage cut-out relays, which will automatically insert resistance in the exciter field circuits and thus prevent an excess voltage rise.

Where two or three units are used, each exciter should have a capacity sufficient to excite two generators, while with four or more units it will undoubtedly be more advantageous to make the capacity of each exciter correspond to the excitation requirements of one generator and provide a spare motor-driven exciter. This may then have the same capacity as one of the direct-connected exciters or, for larger stations, it may have twice the capacity, or two sets may be installed.

The question of economy should, of course, also be considered in deciding whether or not to use direct-connected units. Such exciters will, as a rule, be of a rather slow speed and thus more expensive per kw. than water-wheel-driven units, the difference, however, diminishing as the head and number of units increase. On the other hand, water-wheel-driven exciters involve the cost of the hydraulic equipments, besides the additional expense of the building caused by the space occupied by these units. On the whole, however, direct-connected units are more efficient.

In connection with exciters driven by separate turbines or direct-connected to the main generator, the question of runaway speed must be carefully considered, as this may have an important bearing on the choice of exciter, especially with high-speed units, where special designs may have to be resorted to on this account.

With individual exciter systems each main generating unit is provided with its own exciter. As these are not operated in parallel, no exciter bus is required, although in large and important stations it might be desirable to provide an emergency excitation bus with a reserve motor-driven exciter, so that any generator field may be thrown on this bus in case of trouble with one of the individual exciters.

Individual exciters may be either direct-connected to the main generators or motor driven, and each, as a rule, need only be of a capacity sufficient to excite the field of its own unit. For stations containing only a small number of units it might be desirable to provide the reserve capacity by making the direct-connected exciters large enough to excite two generators. On the other hand, with a large number of units with motor-driven exciter it may be considered sufficient to keep a spare motor exciter set which can quickly be exchanged for any damaged set.

Individual direct-connected exciters are, of course, subject to the same considerations as previously explained under the common system. While they insure a very reliable and simple system, with a large number of slow-speed generators, motor-driven exciters, as described in the following, may prove more economical.

Such exciters can obviously be selected to run at the most economical speed. The power may be supplied from the main bus through step-down transformers, if necessary; but in several large and important plants provision has been made for an auxiliary power supply entirely independent of the main system. This generally consists of two water-wheel-driven A.C. generators, each having a capacity sufficient to supply power for all the motor-driven exciters, as well as for other station auxiliaries. Provision should also be made for supplying power to the auxiliary bus, in case of emergency, from the main A.C. bus. This usually involves step-down transformers, as the auxiliary generator voltage should be chosen to correspond to the most desirable motor voltage. The auxiliary generators are generally provided with their own individual direct-connected exciters.

The individual exciter system, with motor-driven exciters supplied from separate water-wheel-driven auxiliary alternators, solves the problem of excitation and auxiliary power in the most effective manner. Not only is the exciter system free from disturbances on the main system, but it provides a very reliable independent source of auxiliary power. This is important, especially when starting up the plant; at such times, power is required for operating governor pumps and other auxiliaries, and cannot, of course, be supplied by the main generators.

The use of the exciters as a source of auxiliary power is not considered good practice and should be avoided.

Figures 223 to 225 show diagrams of connections of three different arrangements. In the system shown in Fig. 223 there are three exciters, two of which are water-wheel-driven, the reserve being motor-driven. Only one set of exciter busbars is shown, although frequently an auxiliary set is also installed. The equalizer connection and the exciter fields are left out, so as to simplify the diagram. Means are provided for sectionalizing the bus, as shown. Power for the induction motor is taken from the main bus, and any number of motors can be

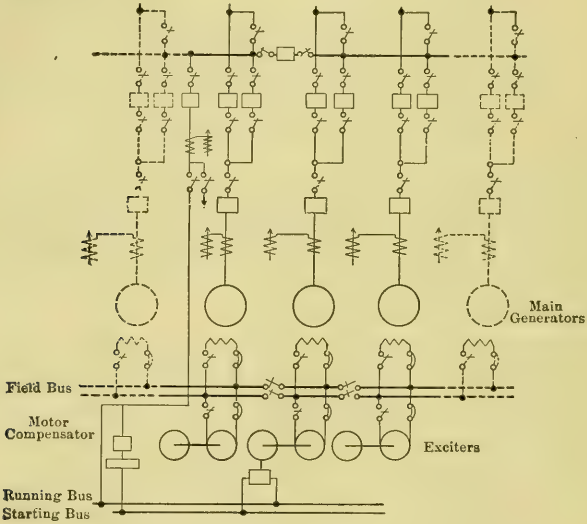


FIG. 223.—System of Exciter Connections.

started by one compensator if a common running and starting bus is provided.

Figure 224 represents a comparatively large system with not less than six direct-connected exciters operating in parallel. There are two sets of busbars, one for excitation and the other for emergency or auxiliary service, and switches are provided so that the exciters can be connected to either set as desired. One exciter can, if necessary, be connected to the auxiliary bus while the others are operating on the field-bus. As previously stated, however, it is not considered good practice to use the excitation system for the auxiliary service. To provide spare capacity for the system shown, a motor-driven exciter can be installed, feeding the auxiliary bus, and the field switches made double-throw instead.

Figure 225 shows the connections of an installation with individual motor-driven exciters for each main unit. The exciters, which have a capacity corresponding to that required by their respective generators, are not operated in parallel, but have their terminals connected directly

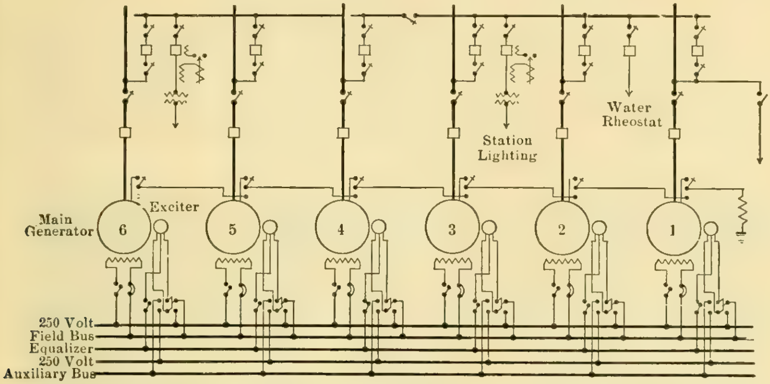


FIG. 224.—System of Exciter Connections.

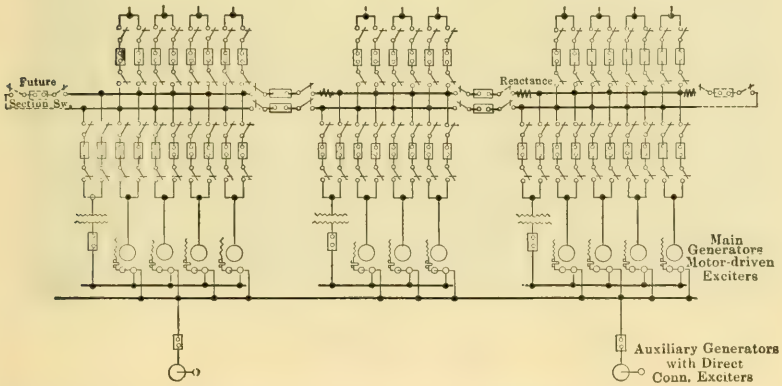


FIG. 225.—System of Exciter Connections.

to the generator fields through the collector rings. The regulation is accomplished by adjusting the exciter fields (see Voltage Regulation), thus eliminating large field rheostats in the main field circuits. The exciter sets (Fig. 226), receive their driving power normally from an entirely independent source, consisting of two auxiliary water-wheel-driven low-voltage alternators with their own individual direct-connected exciters (Fig. 227). These alternators feed into a set of busbars, to which the exciter motors are normally connected. Provision is also

made, however, for feeding the exciter sets from the main bus. One step-down transformer is provided for each bus section and supplies power to an auxiliary exciter bus which is sectionalized in the same number of groups as the main bus. Connection can also be established (not shown in diagram), in case of emergency, with a storage battery which ordinarily is used for the operation of the oil switches.

In another, somewhat similar installation, the supply system for the exciter sets consists of two low-voltage generators arranged for combination drive, one end being connected to a water wheel and the other to an induction motor which obtains its driving power through step-

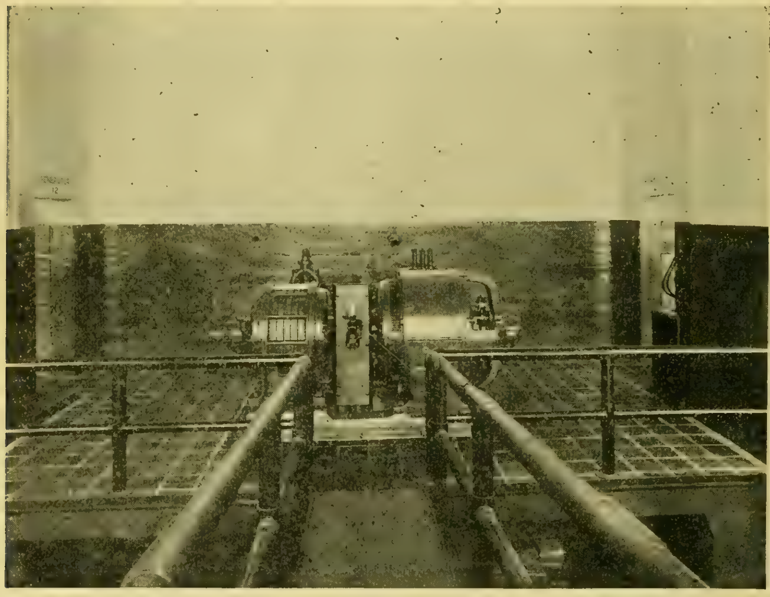


FIG. 226.—Exciter Set for Generating Unit in Mississippi River Power Company's Plant at Keokuk.

down transformers from the main buses. The water wheel is used for normal operation.

Modifications of the two last systems mentioned above are found in some of the most recent installations. For example, in the Queenston plant of the Ontario Power Company at Niagara Falls, the principal source of the excitation of the 45,000 kv.a. generators is a direct-connected exciter mounted above the generator and of a capacity corresponding to the excitation required by it. The auxiliary source of excitation consists of motor-generator sets of a capacity to carry the excitation of any one of the generators and to work with the voltage

regulator belonging to that unit. One such auxiliary exciter will be used for a group of several machines, and each spare exciter may be connected to its own bus, to which the field of any generating unit of its group may be connected. These reserve exciters are driven from two independent turbine-driven 2300-volt service generators, which also supply power for all the other station auxiliaries.

A very interesting arrangement for providing excitation and auxiliary power is that contemplated for the new 70,000 horse-power units in the Hydro-Electric Power Company's plant at Niagara Falls. Each of the main generators, which will have a capacity of 65,000

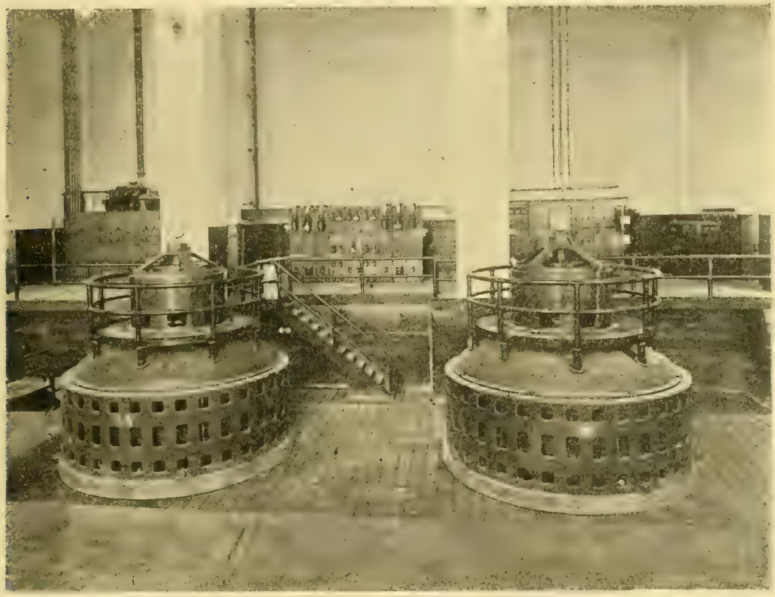


Fig. 227.—Auxiliary Generators with Direct-connected Exciters. Power Supply for Motor-driven Exciters shown in Fig. 226.

kv.a., is to include a small A.C. service generator on the main shaft of the main unit. This auxiliary generator will be of sufficient capacity to supply all the auxiliaries for the unit, including a motor-driven exciter set, governor pump and any other equipment that may be required. All the auxiliaries will be arranged for starting from the A.C. service bus. The motor-driven exciter set will include two exciters, one for the main unit and a smaller one for exciting the field of the auxiliary generator. After the exciter set and the main unit have both been started and the auxiliary generator excited, the auxiliary A.C. supply will be transferred from the service-bus feeder to the auxiliary generator.

In view of the very large capacity of the main units involved, it was considered advisable that they should be made complete individual power plants in so far as possible.

Rheostats. For common exciter systems, it becomes necessary to provide rheostats for regulating the field current both of the exciters themselves and of the main generators.

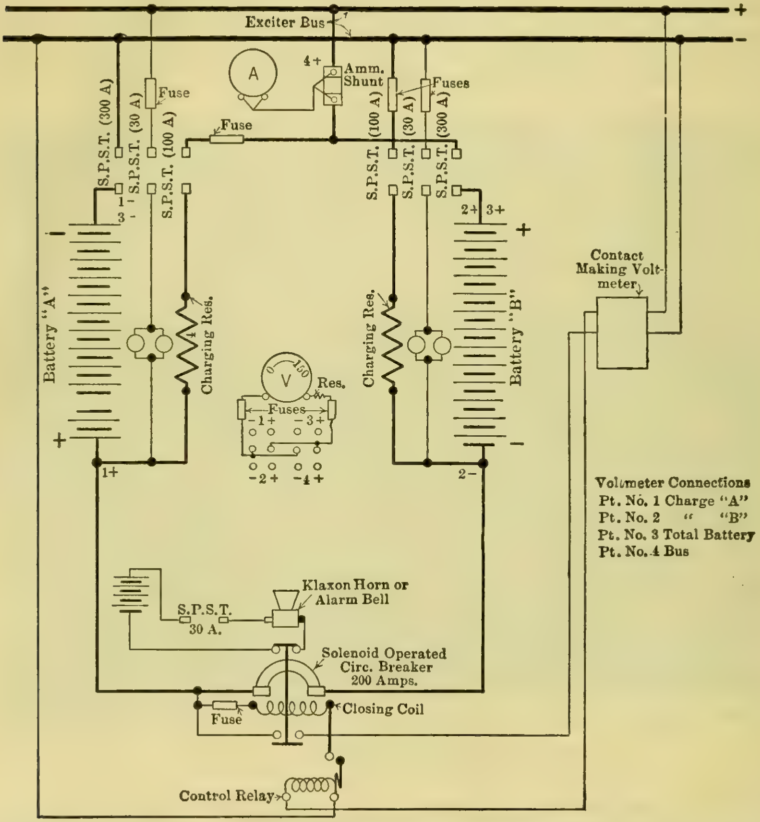


FIG. 228.—Diagram of Connections for Exciter Battery for Emergency Service. Normally Off Line.

With individual exciters, the alternator field rheostats may be omitted, but it is generally considered better practice to install them for emergency use in case some other source of excitation must be resorted to. A somewhat more stable operation at lower voltage ranges will usually also be obtained when main field rheostats are used, as this will enable the exciters to be worked at somewhat higher voltage.

Exciter Batteries. Storage batteries are occasionally used as a reserve source for field excitation. The method of connecting and operating such batteries varies somewhat with the arrangement adopted for furnishing the normal supply of exciting current, and the method employed for controlling the field excitation. Where the exciting current for all of the machines is taken from a common exciter bus, the battery would ordinarily be floated directly across this bus, provided its voltage is substantially constant. If the exciter bus voltage is varied from time to time by manual control, the battery can still be kept constantly connected to the bus, but the number of cells in circuit must be adjusted by means of an end cell switch whenever the exciter bus voltage is changed.

If the exciter bus voltage is constantly varied automatically, as by T.A.-regulator control, the battery cannot be connected directly across the bus. In such a case, two different methods of handling the battery have been used. The first consists in providing a constant-potential exciter bus to which the battery is normally connected, and introducing between this bus and the common excitation circuit a booster whose voltage is automatically controlled by the T.A. regulator. This system is described in detail in the section on "Voltage Regulation," page 369.

The second method consists in connecting the two outer terminals of the battery to the corresponding sides of the exciter bus and opening the battery circuit in the middle, with an automatic switch at this point for connecting the battery in one series in case of failure of the normal source of exciting current. The two halves of the battery are provided with a trickling charge to keep the cells in a healthy and fully charged condition, by connecting through high resistance to the opposite side of the bus, as shown in diagram, Fig. 228.

Where there is no common excitation circuit, but each alternator is provided with its own independent exciter, a different arrangement is adopted. In such a case there is an emergency exciter bus to which the battery is normally connected and to which a spare exciter may be connected when required. Should the source of excitation for any one of the alternators fail, its field circuit is automatically connected to the emergency exciter bus and the spare exciter may then be started up, if it is not already in service, to relieve the battery as soon as this can conveniently be done.

5. VOLTAGE REGULATION

Hand Regulation. The simplest system of regulation is by means of hand-operated rheostats connected in the field circuits of each generator. The pressure of the exciter bus is then generally kept constant

at the rated exciter voltage, and all the regulation is done by manipulating the generator rheostats. In order to regulate the exciter voltage it is, of course, also necessary to provide rheostats in the exciter fields.

T.A. Regulator. Of the various schemes proposed for automatic voltage regulation, the T.A. regulator is now most widely used. With this system the desired A.C. voltage is maintained constant by rapidly opening and closing a shunt circuit across the exciter field rheostat, thus varying the exciter voltage to meet the excitation requirements of the generator.

Method and Cycle of Operation. An elementary diagram of the type T.A. regulator connections with an alternating-current generator and exciter is shown in Fig. 229. The regulator has a direct-current control

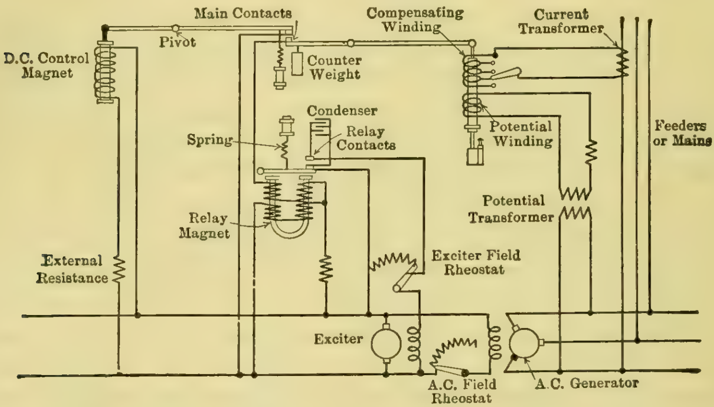


FIG. 229.—Elementary Connections of Type T.A. Automatic Voltage Regulator.

magnet, an alternating-current control magnet, and a relay. The direct-current control magnet is connected across the exciter bus and provided with two cores, the lower being a fixed stop core, the upper a movable core attached to a pivoted lever at the opposite end of which is mounted a flexible contact. The pull of the magnet is shown in the diagram as if opposed by one spring, but in practice there are actually four springs in multiple, that pick up at different exciter voltages. A differentially wound relay magnet is also shown connected to the exciter bus, one winding being permanently connected to the bus, while the other is arranged to be opened and closed by the main contacts. The relay has a pivoted armature to which a spring is attached to oppose the pull of the magnet. The contacts are connected across the exciter field rheostats. Condensers are connected across the contact points to prevent destructive arcing.

The potential winding of the alternating current control magnet is shown connected across the generator bus through a potential transformer, while the opposing or compensating winding is shown connected to a current transformer in the feeder circuit. This magnet is of the ordinary solenoid type, having a laminated iron core which is attracted upward by the magnetizing force. The core is attached to a pivoted lever, at the opposite end of which a counterweight is supported, to assist in bringing the lever and core to a point of equilibrium; and on the same end of this lever is shown the lower main contact which, in combination with the upper main contact, produces what are known as the floating main contacts.

It will be seen from the foregoing that the exciter voltage is controlled by the rapid opening and closing of the relay contacts. The value of the voltage depends upon the position of the A.C. magnet core and lever arm, which in turn is dependent upon the value of the alternating voltage being held. At any constant load, speed, and power factor, the A.C. magnet core does not actually move, and the regulator acts as a direct-current regulator maintaining the proper exciter voltage to give the correct alternating voltage. Should the power factor change, or should a heavy load be thrown upon the alternator, the previous exciter voltage will then not give the correct alternating voltage; therefore, the A.C. core will drop slightly. This forces the lower main contact against the upper main contact, which in turn closes the relay contacts. This, as previously explained, causes the exciter voltage to increase. The travel of the A.C. magnet core will continue until the exciter voltage has reached a value corresponding to that required to give normal A.C. voltage under the new conditions. The D.C. side of the regulator will then operate and maintain the exciter voltage at this high value in order to again hold the proper A.C. voltage. In case the load drops on the A.C. generator, the reverse action takes place, and the regulator maintains a lower exciter voltage, in order to give the correct alternating voltage.

The number of relays varies according to the number and size of the exciters, and while the fundamental principle of operation of all the forms of T.A. regulators is the same, certain modifications are necessary.

The regulator may be mounted on the switchboard or on pedestals, as in Fig. 230, this particular form being suitable for twenty-four relays, divided into two groups.

Regulator Arrangements. The most generally used regulator arrangement consists of one common regulator for several exciters operating in parallel. Such a regulator should have sufficient capacity to take care of all the exciters, whether it is necessary to operate them all

at one time or not. Equalizing rheostats must also be provided with such an arrangement in order that each exciter shall carry its share of the load. The full field voltage of one exciter may, for example, be considerably higher than another and it may build up quicker when its rheostat is short-circuited by the automatic regulator. Assuming that the field rheostats of the two exciters are set so that, with the regulator contacts open, the voltages are equal, the more sluggish exciter will tend to maintain its voltage at a lower point than the more active one. The contacts, of course, open and close at the same speed on both. The more active exciter would, therefore, tend to take more than its share of the load. To cause proper division, the resistance in the field circuit of the more active machine should be increased. When an exciter requires more than one relay, the resistance of its field rheostats is divided between the relays and a change in position of the movable arm would unbalance the load on the different contacts. An external resistance called the equalizing rheostat is, therefore, provided and inserted in the field circuit of the more active exciter (usually the higher speed), as shown in the diagram. Equalizing rheostats are required for all but one of several exciters in parallel. Compound-wound exciters in parallel are also provided with equalizer connections in the same way as other D.C. generators.

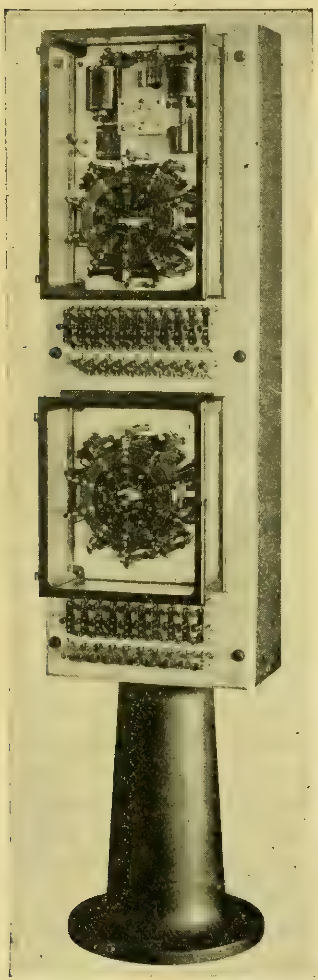


FIG. 230.—Type T.A. Automatic Voltage Regulator Mounted on Pedestal.

It is also possible to operate a common regulator in connection with two or more exciters when these are not operated in parallel on the exciter bus. With certain modifications, the connections are just the same as if the exciters were in parallel. If the exciters to be thus operated have similar characteristics, very satisfactory regulation will probably be obtained over the whole saturation range; but if the exciters have different characteristics, it may happen that if satisfactory

parallel operation of the alternators is obtained at one point of the saturation curve of the exciters, successful operation will probably not be obtained at a different point. Under various load conditions it will, therefore, be necessary for the operator to adjust either the generator field rheostats or the equalizing rheostats, which should be provided as with the previous arrangement.

A third arrangement is that of individual regulator operation. In large central stations, where there are installed a large number of A.C. generators and exciters, and it is desired to operate the generators

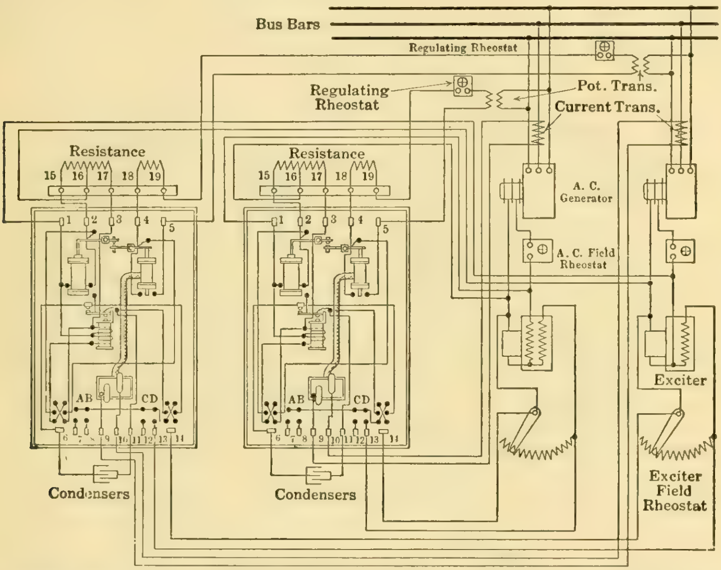


FIG. 231.—Individual T.A. Regulator Operation with Exciters not in Parallel. Main Generators Operating in Parallel.

in parallel but not the exciters, each exciter being arranged to excite its own individual generator (see Fig. 225, page 359), it is possible to operate a voltage regulator on each combination of generator and exciter. The generator, exciter and regulator then form an operating unit, and can be operated without affecting the operation of the other units. This is accomplished by simply placing a current transformer in the opposite phase from that to which the potential transformer for each regulator is connected (Fig. 231).

At unity power factor the phase angle between the current and the potential transformer acting on the regulator magnet core is 90° and the current winding of the regulator has very little effect upon the

voltage of the regulator. However, should the voltage of one alternator tend to increase above that of any of the others, a circulating current would flow between this alternator and the ones having the lower voltage. This exchange current, of course, would be out of phase with the voltage and, therefore, would swing the current in the current coil of the A.C. magnet in phase with that of the potential coil of this magnet. This would cause the regulator on this unit to reduce the generator voltage, which would eliminate the possibility of any cross currents between the different alternators operating upon the busbars. If the voltage on one machine tended to drop, the regulator would operate in the opposite direction, causing the voltage on this generator to rise, which would also eliminate the above-mentioned cross currents.

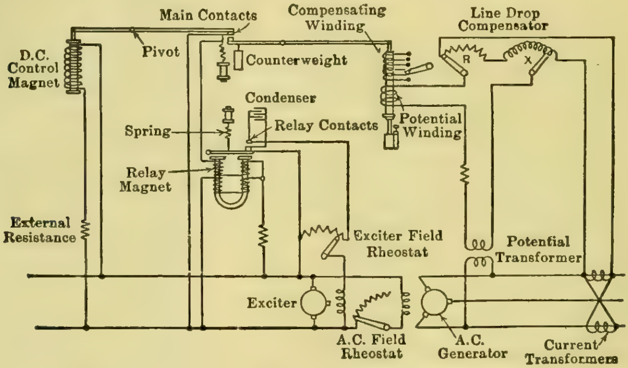


Fig. 232.—Connections for Line Drop Compensator.

Very complete instruction for the connection and operation of the different forms of T.A. regulators can be obtained from the manufacturer.

Line Drop Compensation. Compensation for line drop may also be obtained with these regulators. For ordinary installations, the compensating winding on the alternating current control magnet is connected to a current transformer in the main feeder. A dial switch is provided by which the strength of the alternating-current control magnet may be varied, and the regulator made to compensate for any desired line drop up to 15 per cent, according to the line requirements.

This arrangement is very satisfactory for general use; but where the power factor of the load has a wide range of variation, as in transmission lines, better results can be obtained with a special line drop compensator, adapted to the regulator. This compensator (see diagram, Fig. 232), has two dial switches which are connected to a number of taps of a resistance and a reactance coil, so that the value of these can be

adjusted to compensate accurately for line losses with loads of varying power-factor.

KR System of Regulation. This system is particularly adapted to plants where it is necessary to maintain a constant exciter voltage, as in cases where it is desirable to operate motors and other auxiliary station apparatus from the exciter bus. This system also permits the use of a storage battery in multiple with the main exciters.

By referring to Fig. 233 it will be noted that there is a third bus employed and a D.C. booster connected between this bus and one of

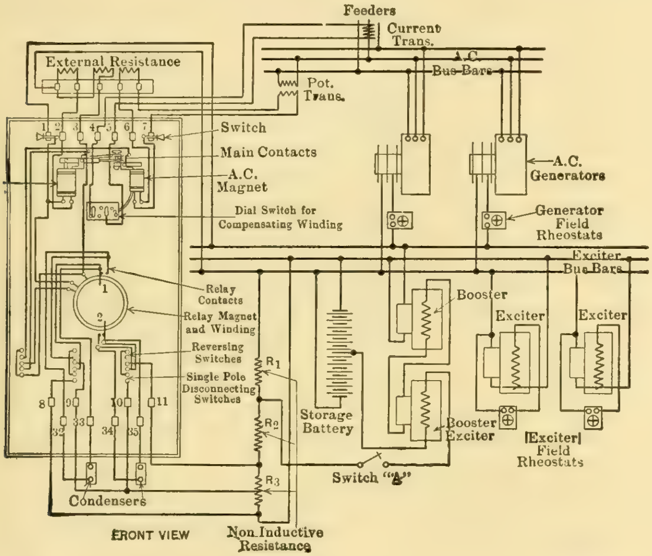


FIG. 233.—Type T.A. Voltage Regulator in Connection with KR System of Regulation.

the exciter buses. The main generator fields are then connected across the outside bus, the voltage of which is determined by the voltage of the booster. This booster is usually excited from a separate exciter whose field is connected from the neutral of the above-mentioned battery and the neutral of a set of resistances marked $R-1$, $R-2$, and $R-3$, respectively. These resistances in series are connected in parallel with the storage battery and the main exciter. The booster exciter field connection is made between resistance $R-1$ and $R-2$, while resistance $R-3$ is short-circuited by means of the regulator relay contacts. These resistances are so proportioned that $R-1$ is considerably greater than $R-2$, and that $R-2$ plus $R-3$ is greater than

$R-1$. It will be readily seen that when $R-3$ is short-circuited by the regulator contacts the direction of excitation upon the booster exciter field will be in one direction; and when this resistance $R-3$ is inserted in circuit by means of the relay contacts being open, the direction of excitation through the exciter field will be in the opposite direction.

The design of the above resistance is also such that there will be full excitation upon the booster exciter in each instance, making it possible to obtain the full boosting and bucking condition upon the main D.C. booster. Assuming that the voltage of the main exciters is 250 and that the D.C. booster is capable of giving 50 volts in each direction, it will at once be noted that the voltage obtainable across the main generator

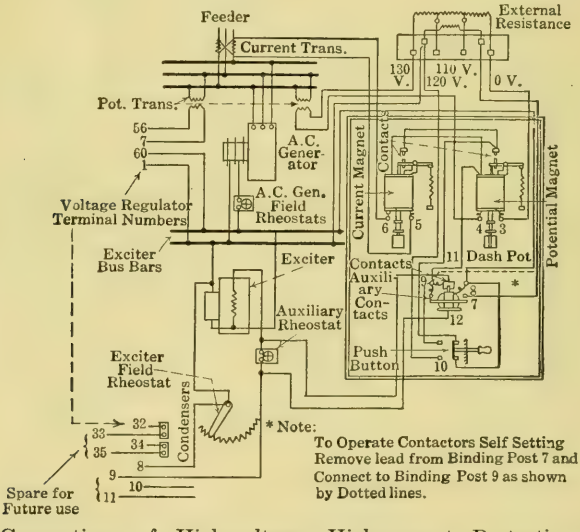


FIG. 234.—Connections of High-voltage, High-current Protective Relay with Type T. A. Voltage Regulator.

fields will be from 200 (the difference between 250 and 50) to 300 volts (the sum of 250 and 50 volts).

High-voltage, High-current Relays. A protective relay has been devised to be used in connection with T.A. regulators for guarding against short circuits and voltage rises in transmission systems. If a voltage regulator is used and a short circuit should occur somewhere on the system—for example, in the transmission lines—the action of the regulator would naturally be to deliver the maximum excitation to the fields of the exciters and generators, so as to keep up the voltage of the system. This, in turn, necessitates that the governors of the prime movers be wide open, and if the short circuit should be sud-

denly relieved, the voltage often rises to very high values, owing to the time element involved in closing the governors and in demagnetizing the fields. The connections for a high-voltage, high-current relay operating in connection with two exciters and one T.A. regulator are shown in Fig. 234. The relay is provided with a current coil and a potential coil, and will automatically insert resistance in the exciter field and thus reduce the exciter voltage in case of excessive loads or voltages on the main system.

Synchronous Condenser Regulation. The question of regulation of large high-voltage systems involves a number of problems not encountered in low-voltage work. In the latter case the energy loss is generally the limiting factor, and the regulation can often be improved by installing larger conductors, which at the same time will reduce the line loss. With high-voltage systems the gain of doing so is very slight, and other means must be resorted to for keeping the regulation within commercial limits. The effect of the inductance and capacity of the line causes the voltage to vary within very wide limits from full to no load. At no load the large capacity current causes a rise of voltage from the generating station to the receiving end, while at full load the lagging inductive current taken by the load, in general, more than offsets the effect of the capacity current and causes a drop of voltage from the generating station to the receiving end. It is evident, then, that by installing a synchronous condenser at the receiving end and by taking advantage of the characteristics of this machine, the receiving voltage can be kept constant at a determined value or approximately so, by adjusting the synchronous condenser field, and thus, by varying the power factor, causing the condenser to draw a lagging current from the line at no load and a leading current at full.

The automatic regulation of the condenser field current is readily accomplished by means of a T.A. regulator. In this instance the regulator does not, therefore, hold a constant power factor, but, by varying the same, holds a constant A.C. voltage provided there is the proper capacity in the synchronous condenser upon which it is operating. The regulator endeavors to hold just as much leading current upon the condenser as there is lagging current upon the main transmission line; or else it will endeavor to maintain the proper lagging current to counteract the effect of any leading current that exists upon the transmission system. The connections and adjustment for the regulator are the same as when it is used upon an A.C. generator, with the exception that greater care should be exercised in the adjustment.

In a system of this kind, if the synchronous condenser has not ample capacity, there is danger of burning out the fields, due to the fact

that the regulator is trying to maintain constant A.C. voltage upon the system. It is very important, therefore, that the highest safe voltage at which to operate the condenser fields be determined, and the regulator adjusted for this limiting value, which may be about 135 volts for a 125-volt excitation.

The regulator, then, cannot hold a higher voltage than 135; and should the voltage reach this value and tend to go higher, the regulator would maintain a constant exciter voltage of this value of 135; but the A.C. voltage would necessarily drop, owing to the fact that it would be requiring a higher exciter voltage than this value in order to maintain the A.C. voltage for which the regulator might be adjusted. The above value of 135 is selected only as a matter of convenience, and the regulator may be set for any value to which it is safe to operate the condenser fields. If they can be operated to as high as 145 volts the regulator should be adjusted at 145 instead of 135.

Similarly, if the regulator is controlling a synchronous motor, the system voltage may rise to a higher value than normal, in which case the regulator would tend to reduce the motor excitation, making it draw lagging current, in an attempt to hold down the voltage. If the motor is also carrying some load, there is a possibility of its dropping out of step unless the regulator is prevented from reducing the excitation too low. To make this adjustment it is first necessary to determine the minimum field voltage at which it is advisable to operate the motor, which may be, say, 40 volts. The regulator is then set for this minimum voltage, and if the adjustment is properly made there should be no possibility of the regulator causing the motor to fall out of step.

For a further study of the subject of "Synchronous Condenser Regulation," the reader is referred to an article by F. W. Peek, Jr., in the *General Electric Review* for June, 1913.

6. TRANSFORMERS

Fundamental Principles. A constant potential transformer consists essentially of an iron core upon which are wound two windings, a primary and a secondary. When one winding is connected to an alternating-current supply of power, an alternating magnetic flux is excited in the iron core and an alternating voltage is induced in the secondary winding, as its turns are surrounded by the same flux as the primary. If the secondary winding is now closed through a resistance or other load, a current will flow therein.

In an "ideal" transformer, power would be transmitted from primary to secondary without any loss. In actual practice, however,

this is not quite possible on account of the losses which take place in the iron core and the windings. Similarly, in an ideal transformer, the ratio of primary to secondary voltage would be equal to the ratio of the number of turns in the respective windings. In a real transformer there is, however, also a voltage drop caused by the resistance and leakage reactance of the windings. This reactance is due to the leakage flux which links with the turns or part of the turns of one winding only.

The action of a transformer can best be understood by means of a vector diagram Fig. 235. Consider first the open-circuit condition, i.e., no current flowing in the secondary winding. The primary E.M.F. OB_1, causes an exciting current OM_1 to flow, this current consisting of two components MM_1, and OM. The component MM_1 is in phase with the E.M.F. and supplies the iron core loss due to hysteresis and eddy currents, while OM, which is in quadrature with the E.M.F., represents the magnetizing current and is thus in phase with the flux. The secondary E.M.F. OB_2 is exactly opposite the primary in phase, and its value is equal to that of the primary times the inverse ratio of the turns of the two windings.

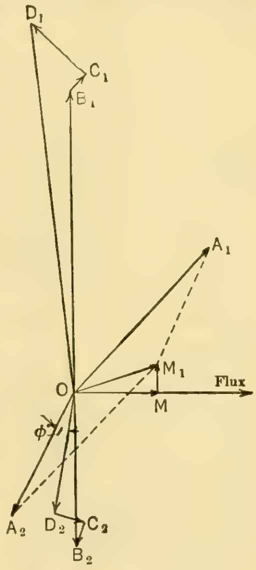


FIG. 235. — Theoretical Transformer Diagram.

Suppose, now, that the transformer is loaded, in which case a secondary current OA_2 will flow, proportional to the load. If the load was non-inductive this current will be in phase with the secondary terminal E.M.F. OD_2, thus lagging behind the induced E.M.F. OB_2, due to the leakage reactance. In this particular case, however, the load is inductive and the current OA_2 lags behind the terminal E.M.F. $OD_2\phi$ degrees, the corresponding power factor of the load being cos ϕ. The secondary terminal E.M.F. OD_2, is less than the induced E.M.F. OB_2 on account of the resistance drop B_2C_2 and the reactance drop C_2D_2. These values are the product of the secondary current times the resistance and the reactance, respectively, of the secondary winding, the former being in phase with the current and the latter in quadrature.

When the secondary current flows, it disturbs the equilibrium by tending to demagnetize the core, and the primary current increases, until, in addition to the exciting current OM_1, a current flows, the magnetizing effect of which just balances the magnetizing effect of the

secondary current. This additional current is represented by M_1A_1 and it is just equal and opposite to the secondary current OA_2 times the inverse ratio of the number of turns in the windings.

The total primary current OA_1 is, therefore, seen to be composed of the exciting current OM_1, which is practically constant for all loads and the load current M_1A_1. The impressed primary E.M.F., OD_1, is a little greater than the primary counter E.M.F., OB_1, on account of the resistance drop B_1C_1 and the reactance drop C_1D_1, the values being the product of the primary current OA_1 times the resistance and leakage reactance, respectively, of the primary winding. The former is in phase with the current, the latter in quadrature.

Induced E.M.F. The relation between the counter E.M.F. of a transformer and the various factors, such as flux density, number of turns, frequency, etc., are determined by the following formula:

$$E = 4.44 \times f \times n \times \phi \times 10^{-8};$$

in which E = mean effective E.M.F.;

f = frequency in cycles per second;

n = total number of turns of the primary winding;

ϕ = total magnetic flux in maxwells.

This equation is based on the assumption that the E.M.F. is a true sine wave.

Ratio. The A.I.E.E. Standardization Rules state that "The voltage ratio of a transformer is the ratio of the R.M.S. primary terminal voltage to the R.M.S. secondary terminal voltage under specified conditions of load." It also defines "the ratio of a transformer, unless otherwise specified, as the ratio of the number of turns in the high-voltage winding to that in the low-voltage winding, i.e., the turn-ratio."

The two ratios are equal when the transformer does not carry any load. When loaded, the resistance and inductance of the windings cause a drop in the voltage, thus modifying the ratio of transformation slightly.

The ratio of a transformer refers, of course, to the turns which are connected in series, high-voltage as well as low-voltage. In many instances it is desirable for the sake of interchangeability and standardization to split up the windings in groups of sections which may be connected either in series, parallel, or series-parallel. This is almost always the case with distributing transformers, where the low-voltage winding may be connected for 115–230 volts. This makes possible the following connections:

High-Voltage.	Low-Voltage.		Ratio.
	Connection.	Voltage.	
2300	Parallel	115	20 : 1
2300	Series	230	10 : 1

For transformers of very high voltages, it is often requested that the high-voltage winding be designed for series-parallel connection. So, for example, by designing a transformer with a high-voltage of 110,000–55,000 volts, it is possible to operate the system at the lower voltage until the load has increased to a point necessitating a change-over to the higher transmission voltage.

Rating. A transformer should be rated by its kilovolt-ampere (kv.a.) output. This is simply equal to the product of the voltage and current, and is, therefore, the same whether the different coils are connected in series or parallel. If the load is of unity power factor, the kilowatt output is the same as the kilovolt-ampere output, but if the power factor is less, the kilowatt output will be correspondingly less. For example, a 100 kv.a. transformer will have a full-load rating of 100 kw. at 100 per cent power factor, 90 kw. at 90 per cent power factor, etc.

Regarding the rating of a transformer, the A.I.E.E. Rules give the following definitions:

"The rated current of a constant potential transformer is that secondary current which, multiplied by the rated load secondary voltage, gives the kv.a. rated output. That is, a transformer of given kv.a. rating must be capable of delivering the rated output at rated secondary voltage, while the primary impressed voltage is increased to whatever value is necessary to give rated voltage."

"The rated primary voltage of a constant potential transformer is the rated secondary voltage multiplied by the turn ratio."

In consequence of the above rule, the normal primary operating voltage when the transformer is delivering load is greater than the rated primary voltage by the regulation drop. At unity power factor, this variation from rated voltage is negligible, and for that reason, no attempt is made to allow for it in the ratings of the majority of transformers. In certain cases, however, where high internal reactance is combined with operation at low power factor the difference between the rated primary voltage and normal operating voltage is appreciable. Such cases are taken care of by specifying two primary voltages, the

rated primary voltage as defined above and also an operating primary voltage, at a specified load and power factor.

It should be noted that the rated high-voltage and rated low-voltage are independent of conditions of load, and of whether the high-voltage happens to be primary or secondary. On the other hand, the operating primary voltage is affected by the amount of load, power factor of load, and by whether the transformer is used to step up or down.

The A.I.E.E. Standardization Rules identify self- and water-cooled oil-immersed transformers as to kv.a. rating by their maximum continuous capacity at 55° rise. With an ambient room temperature of 40° C. air for the former, and 25° C. incoming water for the latter, the observable temperatures would be 95° and 80° C. respectively. The rules further specify that the temperature of the windings of transformers is always to be ascertained by Method II, i.e., the resistance method. (See page 307, "Rating of Generators.") This method allows for a correction factor of 10° C., so that for self-cooled transformers the hottest spot temperature is limited to 105° C. and for water-cooled to 90° C. The oil shall in no case have a temperature, observable by thermometer, in excess of 90° C.

For air-blast transformers, the rules specify that a correction shall be applied to the observed temperature rise of the windings, and it is to be noted that air-blast transformers constitute the only instance wherein it is required that a correction shall be applied to take into account the precise ambient temperature at time of the test. This is due to the difference in resistance caused by a difference between the temperature of the ingoing cooling air and that of the standard reference. This correction shall be the ratio of the inferred absolute ambient temperature of reference to the inferred absolute temperature of the ingoing cooling air, *i.e.*, the ratio $\frac{274.5}{(234.5+t)}$; where t is the ingoing cooling-air temperature.

Thus, a cooling-air temperature of 30° C. would correspond to an inferred absolute temperature of 264.5° on the scale of copper resistivity, and the correction to 40° C. (274.5° inferred absolute temperature) would be $\frac{274.5}{264.5}=1.04$, making the correction factor 1.04; so that an observed temperature rise of say 50° C. at the testing ambient temperature of 30° C. would be corrected to $50\times 1.04=52°$ C., this being the temperature rise which would have occurred had the test been made with the standard ingoing cooling-air temperature of 40° C.

In determining the temperature rise by the resistance method, it is obviously impossible to obtain resistance readings at the exact instant

of shutdown, and the observed readings should therefore, be corrected for the drop in temperature occurring between the instant of shutdown and the time when readings are made. Such corrections depend upon the design and are generally given by the manufacturer as so many degrees per minute, assuming an average of three minutes for the measurement.

Efficiency. The efficiency of a transformer is the ratio of the kilowatts output measured at the secondary terminals to the kilowatts input measured at the primary terminals. The difference between these two values equals the losses, which consist of the no-load losses, the I^2R losses and the stray-load losses. The no-load losses consist of the hysteresis and eddy-current or core loss in the laminations, the I^2R loss due to the exciting current and the dielectric hysteresis loss in the insulation. The I^2R losses should include the copper loss in all the windings, primary, as well as secondary, and the stray-load losses consist of the eddy-current loss in the windings and core, due to fluxes varying with the load. They should also include the stray loss in other parts of the transformer.

The no-load losses shall, according to the A.I.E.E. Rules, be measured by wattmeter with open secondary circuit at rated frequency, and with an applied primary voltage giving the rated secondary voltage plus the IR drop which occurs in the secondary under rated load conditions.

The load losses, comprising the I^2R and stray-load losses, shall be measured by applying a primary voltage, at rated frequency, sufficient to produce rated-load current in the windings, with the secondary windings short-circuited. In determining all the losses, care shall be taken that they are corrected to a reference temperature of 75° C.

The efficiency is generally given at unity power factor, but can readily be figured out for any power factor, as the losses are independent of the same as long as the kv.a. is not changed. For example, assume a 1000 kv.a. transformer having a total loss of 14 kw. or 1.4 per cent based on 1000 kw. at unity power factor. Based on 800 kw. 80 per cent power factor, the loss would be 1.75 per cent. In the former case, the efficiency at full-load would be 98.62 and the latter 98.28, which illustrates the importance of basing the efficiency identically.

The efficiency depends upon the voltage and the size of the unit and varies from about 97 to as high as 99 per cent for transformers generally used in hydro-electric work. For 25 cycles the losses are somewhat higher and the efficiency somewhat lower, on account of the larger amount of material required for this frequency as compared to 60 cycles.

Sometimes the all-day efficiency of a transformer is required for comparison, and this may readily be figured from the following simple formula:

$$\text{All-day efficiency} = \frac{\text{kv.a. hours per day output}}{\text{kv.a. hrs. per day output} + 24 \times \text{no-load loss} + \text{No. of hrs.} \times I^2R + \text{stray-load loss}}.$$

Magnetizing Current. The effect of the magnetizing current in transformers sometimes leads to the question of considering its proper limitations. It was previously shown that this current is wattless, with the exception of a small I^2R loss, and has little influence on the values of the total current in the transformer when it is operating at full load; but as the load decreases the effect becomes more prominent until at no-load it is most noticeable, and the power factor naturally very low. This is an important point where a large number of small transformers are operating on a system, and for such cases it has become quite common to limit the magnetizing current to a value not exceeding about 10 per cent of the full-load current, a value which cannot be considered detrimental to the system. For large units it is generally much lower.

There is also another limitation which is given consideration in connection with large transformer units. Such transformers are nowadays built of high-grade steel, which has a much smaller core loss per pound than the material formerly used, and this has in many instances made it advisable to increase the core densities. If, however, these are increased much above the bend of the saturation curve, an unstable operation is liable to follow, and for such conditions, the limitation of the magnetizing current is governed by the permissible core density, usually around 90,000 lines per square inch. With over-voltages causing a saturation of the core, the magnetizing current increases very rapidly, but with the above limitation, based on normal voltage, an over-voltage of around 10 per cent, which is to be expected, should not cause an excessive magnetizing current.

With regard to efficiency and regulation, the effect of the magnetizing current is insignificant.

Voltage. In regard to the use of the terms high-voltage, low-voltage, primary and secondary, the A.I.E.E. Standardization Rules read as follows:

"The terms *high-voltage* and *low-voltage* are used to distinguish the winding having the greater from that having the lesser number of turns. The terms *primary* and *secondary* serve to distinguish the windings in regard to energy flow, the primary being that which receives the energy

from the supply circuit, and the secondary that which receives the energy by induction from the primary."

The terms primary and secondary are, however, often confused, and in order to avoid any misunderstanding it is preferable to use the terms high-voltage and low-voltage instead of primary and secondary.

In every symmetrical three-phase circuit there are two voltages which should be clearly distinguished:

(1) The voltage between lines, called the "delta-voltage" and (2) the voltage from line to neutral, called the "Y-voltage." Under balanced conditions

Y-voltage = delta-voltage divided by $\sqrt{3}$, and
Delta-voltage = Y-voltage times $\sqrt{3}$.

Transformers designed to be suitable for use in either delta- or Y-connection have, as a rule, on the name plates, the line voltages which apply for both connections. The line voltage resulting from Y-connection is followed by the letter "Y"; for example, if the transformer voltage is given $\frac{10,000}{17,300\text{Y}}$, this signifies that both voltages are line voltages but the latter is the voltage resulting when the transformer is connected in Y. The symbol "Y" is used as an abbreviation to indicate that sufficient insulation has been provided so that the transformer may be connected in Y for the line voltage with which the letter is used, but this symbol should not be confused with "Y-voltage." The expressions "delta-voltage" and "Y-voltage" are often loosely used for "voltage when connected in delta" and "voltage when connected in Y," and misunderstandings are often caused thereby. If, however, the facts are kept clearly in mind that a "Y" in the voltage rating of a transformer stands for "Y-connection" and that "Y-voltage" is only a part of the line voltage, there should be no cause for misunderstanding.

The transformer voltage depends, of course, on the nature of the system. The primary voltage of the step-up transformers is, for example, governed by the generator voltage and may be anything up to 13,200 volts. The secondary of the step-up transformers and the primary of the step-down transformers is determined by the most economical transmission voltage, which may be as high as 220,000 volts. The secondary of the step-down transformers is finally governed by the potential of the distributing system. Where this is extensive its voltage may be comparatively high, perhaps 33,000 or even higher, while, for smaller systems it may only be 2300 volts and even lower. The voltages generally used for power transformers are as follows:

Low-Voltage.	High-Voltage.		
2,300	22,000	88,000	220,000
6,600	33,000	110,000	......
11,000	44,000	132,000	......
13,200	66,000	154,000	......

The test voltage which shall be applied to determine the dielectric strength of the insulation is specified by the A.I.E.E. Rules as twice the normal voltage of the circuit to which the transformer is connected plus 1000 volts. The test shall be made at the temperature assumed under normal operation, and the frequency of the test circuit shall not be less than the rated frequency of the apparatus tested. The duration of the application of the voltage shall be one minute, and it shall be successively applied between each electric circuit and all other electric circuits and metal parts grounded. Inter-connected polyphase windings are considered as one circuit, and all windings except that under test shall be connected to ground. Transformers which may be used in Y-connection on three-phase circuits shall have the test based on the delta or line voltage.

The following exceptions to the above rule are given:

(1) Alternating current transformers connected to permanently grounded single-phase systems, for use on permanently grounded circuits of more than 300 volts, shall be tested with 2.73 times the voltage of the circuit to ground plus 1000 volts. This does not, however, refer to three-phase apparatus with grounded neutral.

(2) Distributing transformers for primary pressures from 550 to 4500 volts, the secondaries of which are directly connected to consumer's circuits, shall be tested with 10,000 volts from primary to core and secondary combined. The secondary winding shall be tested with twice normal voltage plus 1000 volts.

Under certain conditions it is permissible to test transformers by inducing the required voltage in their windings, instead of using a separate testing transformer. By "required voltage" is meant a voltage such that the line end of the windings shall receive a test to ground equal to that required by the above general rules.

Induced voltage tests are desirable as a means of testing the insulation between coils, and the manufacturers usually subject transformers to such tests before shipment. The transformers are then excited to twice normal voltage for a period of 7200 cycles at the lowest practical frequency. With a test frequency of 120 cycles, the time would

then be one minute, and with a higher frequency correspondingly less.

Transformers for very high voltages, with graded insulation and with the neutral permanently grounded, can, of course, be tested only by an induced potential test, and it has become general practice to test such transformers at 2.73 times the voltage to neutral or ground.

Transformers with "graded" insulation shall be so marked. The term "graded" is used to indicate the employment of less insulation towards the end of the windings where the insulation stresses are low, i.e., towards the ground, and more insulation at the high-potential ends.

Before the adoption of the sphere gap as a method of voltage measurement, transformers were generally tested by the use of the needle gap. This resulted in more or less inconsistent tests, due mainly to the effect of the variation in humidity and also, to some extent, to temperature, barometric pressure and corona. Accordingly, when needle gaps were used for voltage measurements, the actually applied voltage depended upon the particular season of the year and the atmospheric conditions at that time, with the natural result, in many instances, that the transformer tested did not receive the required voltage. With the adoption of the sphere gap, the variation in the applied voltage is eliminated, and if this method of measurement is insisted upon, it is safe to assume that the full potential is actually applied. This is, of course, of great importance with very high-voltage transformers.

In the section on "Rating," it was shown that transformers are designed to deliver their rated kv.a. capacity at rated secondary voltage. Because the line drop varies with the load and power factor, taps in the primary winding of step-down transformers may be a desirable feature, particularly in units of the larger sizes and for the higher primary voltage ratings. These taps are, in most cases, intended for use in maintaining the secondary voltage at its rated value under the varying conditions of load and power factor. Taps may also be desirable in the step-up transformers, to obtain the desired secondary voltage at full-load without having to boost the generator voltage above normal.

Taps may be either of reduced or full capacity. In the latter case, the current-carrying capacity of the winding which has the taps should correspond to the maximum current at the lowest voltage tap.

Sometimes large power transformers have their high-voltage windings so arranged that the two halves can be connected either in parallel or series. The former connection corresponds to only half the voltage of the latter and is for use during the first period of operation of a system when the load is light and when the lower operating voltage is sufficient. When the load has increased so as to necessitate a higher voltage, the

two windings are connected in series, thereby doubling the transmission voltage.

Where taps are not essential for the satisfactory operation of a system, they should be avoided as much as possible, especially in very high-voltage transformers. It is evident that taps are difficult to insulate and bring out to the connection board, and that they therefore introduce additional weakness in the design of a transformer and thus decrease the reliability of operation.

Induction motors, synchronous motors and synchronous converters started from the A.C. side frequently require transformers with taps for reducing the potential at starting, in order to prevent a heavy

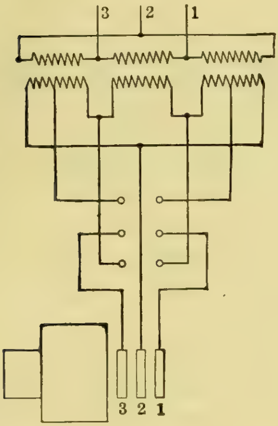


Fig. 236.—A. C. Starting Arrangement Three-phase Synchronous Converters.

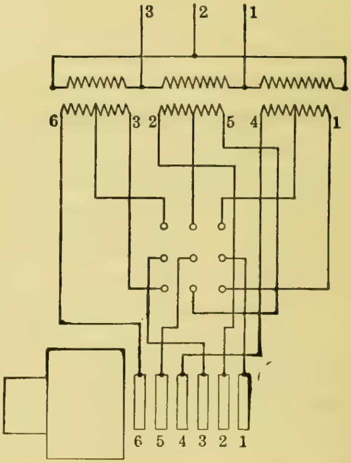


Fig. 237.—A. C. Starting Arrangement Six-phase Synchronous Converters.

rush of current. Figure 236 shows the connections for starting three-phase synchronous converters and Fig. 237 for six-phase converters.

Reactance. The percentage of the total flux that links with the primary but does not link with the secondary winding, plus that which links with the secondary but not the primary, is the per cent reactance of a transformer. Thus, if 95 per cent of the primary flux cuts both primary and secondary, the transformer is said to have a 5 per cent inherent reactance.

The factors affected by the reactance of a transformer are its regulation, parallel operation, mechanical stresses and eddy-current losses. A low-reactance transformer has naturally a better regulation than one of high reactance, especially for highly inductive loads; and in order to obtain a good voltage regulation it was formerly the custom to design

transformers with a reactance as low as $1\frac{1}{2}$ to 2 per cent. Such a low reactance is, however, often detrimental to the safe operation of a transformer from the mechanical point of view. If a short circuit should occur at the secondary terminals of a transformer, and the power supply at the primary is sufficient to maintain the primary terminal voltage, as may be the case in very large generating systems, the primary and secondary currents of the transformer are limited by the impedance only, and, with the exception of very low reactance transformers, it is essentially the reactance which determines the total impedance and thus the short-circuit current.

As the primary and secondary currents are opposite in phase, they repel each other, the force being approximately proportional to the square of the current. It therefore follows that the repulsion, which is small at full load, may reach enormous values under short-circuit conditions if the transformer reactance is low. For example, in a transformer having a 2 per cent reactance the short-circuit will be 50 times normal and the mechanical stresses will increase as the square of this, or 2500 times, amounting to many hundred tons. This clearly illustrates the necessity of a very rigid construction and also the advisability of reducing the short circuit to a safe value. This may be done by increasing the transformer reactance, and modern practice tends toward the use of considerably higher internal reactances than were formerly used. With modern designs, reactances generally run from 6 to 10 per cent and may even be higher for large high-voltage units.

Regulation. The regulation of a constant-potential transformer is defined by the A.I.E.E. Rules as the difference between the no-load and rated-load values of the secondary terminal voltage at specified power factor (with constant primary impressed terminal voltage), expressed in per cent of the rated-load secondary voltage, the primary voltage being adjusted to such a value that the transformer delivers rated output at rated secondary voltage. All parts of the transformer affecting the regulation should be maintained at constant temperature between the two loads, and where the influence of temperature is of consequence, a reference temperature of 75° C. shall be considered as standard. If a change of temperature occurs during the test, the result shall be corrected to the above reference temperature.

For non-inductive load, the regulation varies approximately from less than 1 per cent for large sizes to around 3 per cent for smaller units. For inductive load it is naturally higher. It can be determined by loading the transformer and measuring the change in voltage with change in load at specified power factor. This method is, however, not generally applicable for shop tests, particularly on large transformers.

It may also be computed for any specified load and power factor from the measured impedance watts and impedance volts.

Let P = impedance watts, as measured in short-circuit test and corrected to 75° C.;
E_z = impedance volts, as measured in short-circuit test;
IX = reactance drop in volts;
I = rated primary current;
E = rated primary voltage;
q_r = per cent drop in phase with current;
q_x = per cent drop in quadrature with current.

$$IX=\sqrt{E_z^2-\left(\frac{P}{I}\right)^2};$$

$$q_r=100\frac{P}{EI};$$

$$q_x=100\frac{IX}{E}.$$

Then:

1. For unity power factor, we have approximately:

$$\text{Per cent regulation}=q_r+\frac{q_x^2}{200}.$$

2. For inductive loads, where the power factor ($\cos\phi$) equals m and the reactive factor ($\sin\phi$) equals n.

$$\text{Per cent regulation}=mq_r+nq_x+\frac{(mq_x-nq_r)^2}{200}.$$

Core and Shell Types. Transformers are of two fundamental designs, namely, the shell and the core type. (Fig. 238.) In the shell type the iron circuit surrounds the transformer coils, while in the core type the windings surround the iron core. While the shell-type transformers have been most extensively used in the past, core-type transformers are now rapidly superseding the former type. With the core-type design, the arrangements of cores and the circular coils present a construction which offers a maximum resistance to the mechanical distorting forces. This mechanical strength, combined with the inherent reactance of this type of transformer, produces a unit which is exceptionally able to withstand severe service. Moreover, the circular coils can readily be insulated for the very highest voltages in use. The core-type design also offers many advantages from the purely electrical

point of view, such as greater safety from harmonics and high frequency troubles, greater electrical stability of the neutral, etc. This is especially true in the case of three-phase units. (See also "Mechanical Design," page 436.)

Method of Cooling. Transformers may be divided into three general classes, depending upon the method of cooling, viz., air blast, oil immersed self-cooled, and oil immersed water-cooled. Air-blast transformers depend upon a forced circulation of air over the surface of the core and coils to carry away the heat. They may be built for large

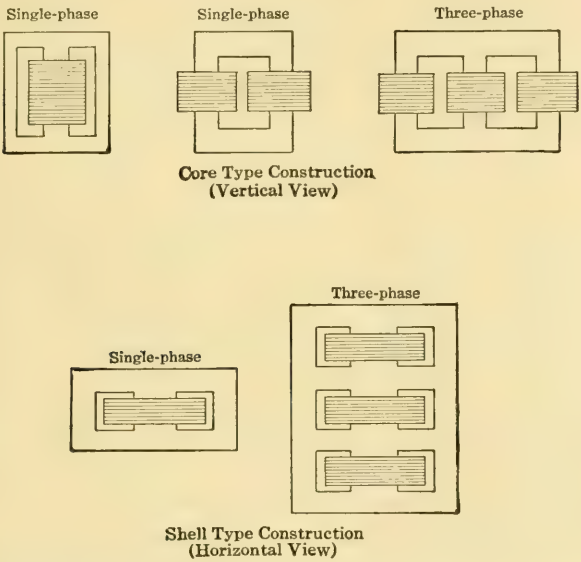


FIG. 238.—Different Types of Transformer Core Construction.

capacities, but the voltage rarely exceeds 30,000 because of the difficulty of insulating them properly.

Oil immersed self-cooled or water-cooled transformers are generally used with hydro-electric power developments, the latter in the generating station, while either type may be used with the sub-stations, depending upon the availability of cooling water. Both types are built for the largest capacities and the highest voltages. Self-cooled oil immersed transformers have the core and coils immersed in a tank of oil, the tank usually being corrugated so as to increase the surface available for dissipating the heat generated in the core and coils. By the addition of external radiators, it is possible to greatly increase the cooling properties of the transformer, and the use of these radiators now makes

it possible to build self-cooled units for very large capacities. Water-cooled oil-immersed transformers depend upon the circulation of water through a coil placed in the top of the tank to carry away the heat from the oil. With about $\frac{1}{3}$ gallon of water per minute per kw. loss, the rise in temperature of the outgoing over the incoming water will be about 10° C.

If operating conditions are such as to give an extended period of low load followed by an extended period of high load and the cost of water is an important item, it may be desirable to use a transformer which will give the necessary low-load capacity as a self-cooled unit and the higher capacity as a water-cooled unit. Such transformers are built with self-cooled tanks but equipped with cooling coils similar to the water-cooled type, and their cost is naturally somewhat higher than the cost of plain water-cooled units of equivalent maximum capacities. No rules can be given, as the transformer may be designed for a low or a high self-cooled rating as compared with the water-cooled rating. Where normal self-cooled designs are equipped with a cooling coil of convenient size, it is usually possible to obtain from 150 to 175 per cent of normal capacity when operating with water and without exceeding the normal temperature rise. This will usually allow of further overloads, either continuous or intermittent, depending upon the normal temperature rise and the reference temperature.

The capacity of self-cooled transformers can also be increased by applying an air-blast to the tank radiating surface. This will naturally result in a lower oil temperature, but care must be taken that the hot-spot temperature does not exceed the permissible value. The increased capacity will as a rule, be given by the transformer manufacturer.

Special precautions must naturally be taken to protect transformers of the outdoor type both from the extreme heat and from the cold in the winter. Protection against heat can readily be obtained by providing sunshades, and in certain instances very good results have been obtained by simply painting the tanks white or light gray. It is more difficult, however, to provide for the cold winter temperatures, especially with water-cooled transformers. With the transformers in service there seems to be no danger of freezing, and if there were, some sort of heating grids could readily be provided in the bottom of the tanks. The main difficulty lies in the formation of moisture which takes place when the temperature of the transformer is allowed to fall below that of the surrounding air; this applies also to indoor transformers. Precautions must, therefore, be taken that this does not happen, either by reducing the water rate at times of cold weather, or by using the cooling water over and over again. An oil with special low freezing-

point may be used in transformers in locations experiencing extreme low temperatures.

Single and Polyphase Transformers. Transformers are made either as single or polyphase units, the latter being generally of the three-phase type. The single-phase design is by far the most flexible, as by different connections any combination can be obtained, and it is then only necessary to provide a smaller reserve capacity than if three-phase units were used. In general, as few transformer banks should be installed as are consistent with reliable operation, in order to reduce the number of high-tension oil circuit breakers to a minimum. At least two banks with single-phase units should thus be provided, and it is of course obvious that transformer banks of a larger capacity can be obtained by using single-phase units. Three-phase transformers are, however, often used, especially where a number of banks are to be used. With such transformers, the connections become simpler and the required floor space less. For spare capacity it becomes necessary to provide an entire three-phase unit.

Three-phase designs may be connected either in delta or Y, and the units may be either of the shell- or the core-type construction. In delta-connected shell-type transformers, should one phase be damaged, it is possible to operate the remaining two phases in open-delta at 58 per cent of the combined capacity, by simply disconnecting the damaged unit of the three single-phase transformers; or, in the case of three-phase shell-type units, by disconnecting and short-circuiting the damaged phase, both high- and low-voltage. This will reduce the flux passing through the part of the core surrounded by these windings and limit the current in the damaged winding to a fraction of the normal full-load current.

Y-connected shell-type transformers of the single- and three-phase types cannot be operated with one phase damaged, except where the neutral is grounded, in which case they may be operated at 58 per cent of their total capacity by short-circuiting both the high- and low-voltage windings of the damaged phase. Such a scheme is not very satisfactory for motor operations, on account of the unbalancing of the phases and the reduced voltage. Lights can, however, be operated successfully by connecting them between the live single-phase wires and the neutral.

In the case of three-phase core-type transformers, even though the windings are delta-connected, it is impossible to operate when one phase becomes short-circuited. This is due to the fact that the three phases are magnetically interlinked in such a manner that any one phase is a return path for the fluxes in the other two phases. This

means that when one phase is short-circuited the short circuit is transmitted magnetically to the other two phases in such a manner that when the two phases are excited large short-circuit currents flow, the short-circuit phase acting as secondary and the remaining phases as primary. In the three-phase shell-type transformer this does not occur, because the fluxes in the three phases are independent of each other, and, therefore, the flux in one phase can be reduced to zero without affecting the other. However, if the damaged winding can be open-circuited or removed from the core, the transformer will operate satisfactorily connected open-delta.

Connections. Among the great variety of transformer manipulations in power and general distribution work, either for straight voltage transformation or for phase transformation, the following are the most generally used:

Voltage transformation:
- Single-phase.
- Two-phase.
- Three-phase, delta—delta.
- Three-phase, delta—Y, and vice versa.
- Three-phase, Y—Y.
- Three-phase, Y—Y delta.
- Three-phase, open-delta.
- Three-phase, T.

Phase transformation:
- Polyphase to single-phase.
- Two-phase to six-phase.
- Three-phase to two-phase.
- Three-phase to three-phase/two-phase.
- Three-phase to six-phase.

Voltage Transformation. *Single-phase.* The windings may be divided into sections and variously connected to meet different requirements. Most standard distributing transformers, for example, are made with two low-voltage coils.

Figure 239 represents the straight connection of two transformers to 1000-volt mains, the transformer consisting simply of single high- and low-voltage windings.

Figures 240 to 242 represent different connections of transformers which are provided with two coils. In Fig. 240, for example, the two low-voltage coils are connected in parallel to supply 100 volts.

In many instances it is deemed advisable to operate a three-wire

circuit from the low-voltage side of transformers, and thereby reduce the cost of copper for the feeders. Such a connection is represented in Fig. 241, where the low-voltage coils are connected in series and their junction connected to the neutral wire. This method of connection is used very extensively and is known as the Edison Three-wire System. When used for combined power and lighting load, the motors are usually

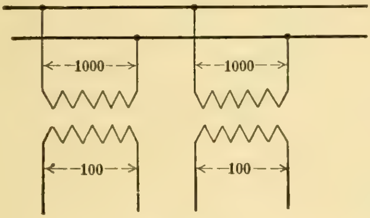


FIG. 239.

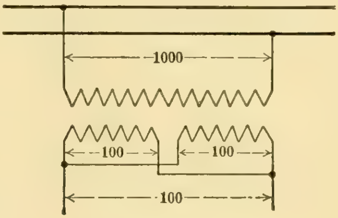


FIG. 240.

connected to the two outside wires, and the lights between the outside and neutral.

The neutral wire generally carries less current than the outside wires, except in the case where the entire load is on one side. The neutral wire should, for this reason, be of sufficient cross-section to safely carry a current which will blow out the main fuses in case of short circuit on one side of the system.

Figure 242 shows the three-wire distribution where a grounded

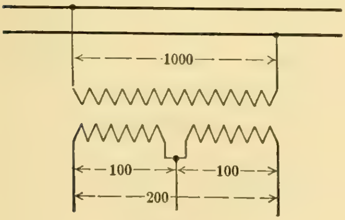


FIG. 241.

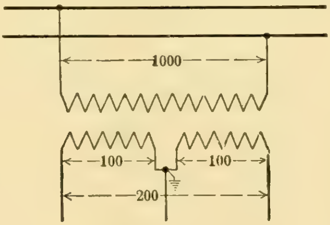


FIG. 242.

neutral wire is employed, this system also being widely used for general distribution, lighting, small motors, etc.

The four terminals of the low-voltage coils are, as a rule, brought outside the case in such proximity that they can readily be connected in any desired manner by joining adjacent terminals. Terminal blocks are seldom used for the low-voltage winding of distributing transformers, because of the large current-carrying capacity required.

The voltage stress on the windings naturally depends on the voltage

of the mains to which they are connected, and also on abnormal operating conditions such as accidental grounds, lightning surges, etc. For the arrangement shown in Fig. 240 it is obvious that under normal conditions the maximum voltage stress between the high-voltage leads is 1000 volts, and to ground 500 volts. If a ground should occur at one of the high-voltage connections to the mains, the stress will be 1000 volts.

In the case of the low-voltage winding, if the two coils are connected in series and non-grounded, the stress to ground under normal conditions is 100 volts, which is also the maximum stress if the junction point or neutral is grounded. If the neutral is not grounded, and one lead becomes grounded, the stress becomes 200 volts. The stress between the two windings is equal to the high-voltage plus or minus the low-voltage, depending on the arrangement and connections of the coils.

In order to avoid the danger of excessive voltages being impressed on the low-voltage circuits, caused by crosses between the high-voltage and low-voltage lines or windings, grounding of the low-voltage circuit is now generally advocated for all voltages up to 250 volts. No point of the circuit can then, except under unusual conditions, rise above its normal potential, and such grounding, therefore, prevents accidents to persons and damage by fire to property. If the low-voltage side, on the other hand, is not grounded, and the transformer breaks down, the high-voltage may be impressed on the low-voltage circuit, and a person touching any bare part of the low-voltage circuit is liable to receive the full shock of the high voltage, if he is grounded by contact with a gas fixture or something of the kind. Furthermore, if the low-voltage side is not grounded and there is a ground on the high-voltage circuit, the high-voltage impressed on the fittings of the low-voltage circuit may cause a fire.

For a two-wire 110-volt circuit it is common practice to connect the ground to one side, while with a three-wire Edison circuit the neutral wire is grounded, limiting the potential from either outside wire to ground to 110 volts. On a 220-volt single-phase power circuit the middle or neutral point of the transformer winding should be grounded.

To prevent any increase of the potential stress between ground and either low-voltage wire, the ground should be well made so that it cannot readily be broken. It should not be fused and should consist of a conductor which, without overheating, can carry a current sufficient to blow the main fuses.

Two-phase. This system practically consists of two separate single-phase circuits, the two E.M.F's. and currents being 90 elec-

trical degrees or one-fourth of a cycle out of phase with each other (Fig. 243).

Two single-phase transformers are mostly used for two-phase systems, and the most common connection is that shown in Fig. 244. The high-voltage windings of the two transformers are connected respectively to the two phases of the supply mains.

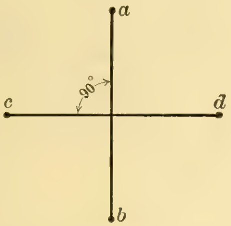


Fig. 243.

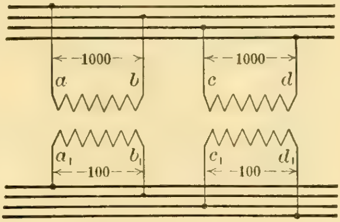


Fig. 244.

It is sometimes also desirable to operate a three-wire two-phase distribution, as shown in Fig. 245. In this case the voltage across the outside wires is $\sqrt{2}$ or 1.41 times the voltage of each individual transformer. This is clearly understood by a reference to the vector diagram in Fig. 246, and is due to the 90° phase difference between the two E.M.F's. so that they must be added vectorially, not numerically.

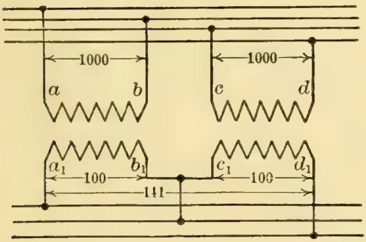


Fig. 245.

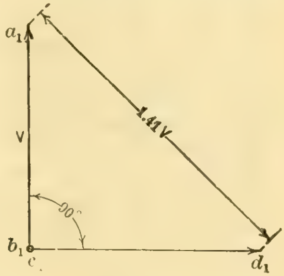


Fig. 246.

The current in the neutral wire is also 1.41 times the current in either of the outside wires, provided the load is balanced.

Transformers in two-phase work are sometimes interconnected, as shown in Fig. 247, where a common return is used on both high- and low-voltage sides. Very few systems are operated on this plan, however.

By connecting together the middle points of the low-voltage windings, as shown in Fig. 248, two 100-volt main circuits are obtained, and also four 70-volt $(50 \times \sqrt{2})$ side circuits.

This method of connection is used when the neutral is to be brought out in connection with Edison three-wire service of rotary converters.

Another two-phase arrangement is shown in Fig. 249, and is commonly called the five-wire system. It is accomplished simply by connecting the low-voltage windings at the middle and bringing out an extra wire from these points.

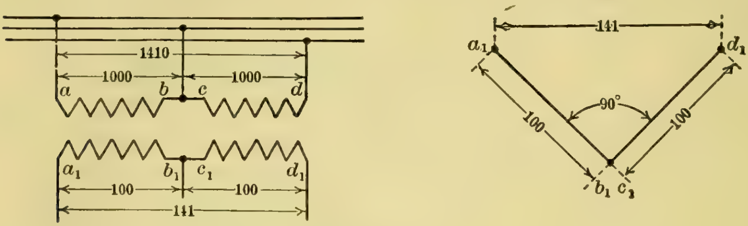


Fig. 247.

With the connections shown in Fig. 244 the maximum insulation stress in case of a permanent ground is 1000 volts on either phase of the high-voltage side, but a simultaneous grounding of one line and a cross between two phases may cause insulation stresses $\sqrt{2}$ times this value or 1414 volts.

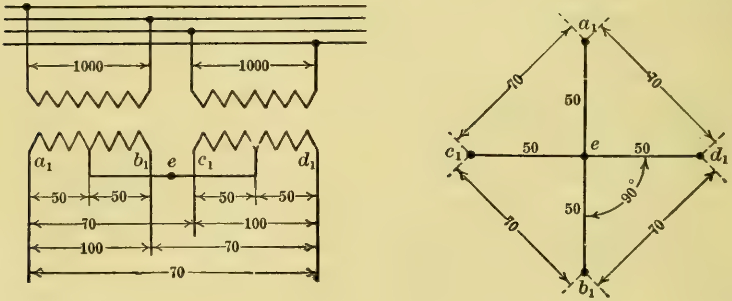


Fig. 248.

With the two low-voltage windings connected for a three-wire distribution, as in Fig. 245, the maximum stress when one of the outside wires becomes grounded is 141 volts, while, if the junction or neutral point is grounded it is limited to 100 volts.

Some systems are supplied with two-phase generators in which the neutral points of each winding are connected together. In this case

simultaneous grounding or connection of any two lines from the generator causes a short-circuit on one-half the generator winding.

For grounding two-phase systems several methods are employed. With a four-wire distribution the mid-point of each transformer winding should be independently grounded unless the motor windings served

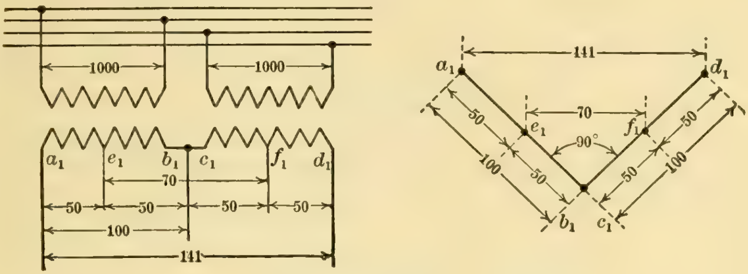


FIG. 249.

are interconnected so as to prevent it. In that event the neutral of one transformer only should be grounded. With the three-wire system the neutral point should be grounded.

Three-phase. The following are the most common methods in which transformers may be connected for a three-phase system:

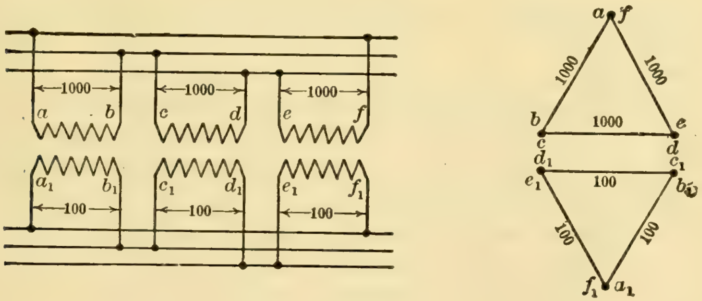


FIG. 250.

Delta-Delta.
Delta-Y, or vice versa.
Y-Y.
Y-Y Delta.
Open-delta.
T-connection.

Delta-delta. With the delta-delta system the leads of three single-

phase transformers are connected to the mains as shown in Fig. 250. The E.M.F's. and currents differ in phase 120 electrical degrees, and the line voltage is equal to the individual transformer voltages. This voltage is commonly denoted the "delta-voltage" to distinguish it from the "star or Y-voltage" in the star-connected combination. Similarly the line current must be distinguished from the current flowing in the closed delta winding.

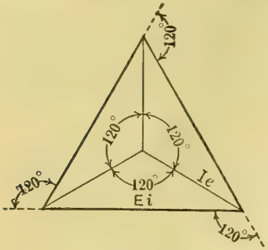


Fig. 251.

The voltage and current relations are easily explained by referring to the vector diagram in Fig. 251.

If we denote: E = delta-voltage, or voltage between phases;
e = Y-voltage, or voltage between phases and neutral;
I = Y-current or line current;
i = delta-current or current in delta winding;

then:

$$E = e\sqrt{3} \text{ or } e = \frac{E}{\sqrt{3}},$$

and

$$I = i\sqrt{3} \text{ or } i = \frac{I}{\sqrt{3}}.$$

When the voltage and current, or line voltage and line current, of a three-phase system are spoken of without further qualifications, the delta-voltage and the Y-current are understood.

Delta-connected transformers must be wound for the full-line voltage, but for only 58 per cent line current. The windings must, therefore, have a greater number of turns than for star connection, while they can be of a smaller size.

The maximum insulation stress in case a permanent ground occurs does not exceed the normal voltage stress.

With a delta-connected 220-volt distributing system the ground connection should be made to the mid-point of the winding of one transformer. This gives 110 volts to ground from the phase wires next to the ground connection and about 190 volts from the other phase to ground.

Where 2200–220-volt transformers are connected delta-delta for three-phase power service, one of the units is occasionally made larger than the other two, and a tap from the middle point of the low-voltage winding brought out so that a 110/220-volt single-phase three-wire service may be obtained for lighting purposes.

If one transformer or one phase of the three-phase transformers is disabled, the other two may then be used in open-delta.

The capacity of a group of delta-connected transformers is equal to

$$\sqrt{3} \times E \times I \text{ kv.a.},$$

where E represents the transformer or line voltage and I the line current. The current in the transformer windings is equal to $\frac{I}{\sqrt{3}}$.

Transformers operating in a three-phase delta-delta bank will take a circulating current if their ratios are different, and will fail to divide the load properly if their respective impedances and the ratios of reactances to resistances are not equal. The circulating current may be calculated as follows:

$$\text{per cent } I_c = 100 \times \text{per cent } e/3 \times \text{per cent } IZ;$$

where per cent I_c = circulating current in per cent of the normal load current;

per cent e = the unbalanced voltage in the delta, is approximately equal to the maximum difference in phase voltages in per cent of the phase voltage. This applies to the windings within the delta, and not to any portion that may extend beyond the delta.

per cent IZ = the per cent impedance of one unit, assuming all three units alike.

The circulating current flows in both the primary and the secondary windings simultaneously.

It is not considered good practice to operate a three-phase delta-delta bank under any one of the following conditions:

1. When the division of load is such that, with a total load on the bank equal to the combined kv.a. rating, the load current in any one of the units is greater than 110 per cent of its rating.

2. When the no-load circulating current exceeds 10 per cent of the rated current of the unit.

3. When the arithmetical sum of the no-load circulating current and the load current exceeds 110 per cent of the rated current of the unit.

The above-mentioned currents are exclusive of magnetizing current and of each other.

Delta-delta-connected transformers having 50 per cent taps brought out (Fig. 252a) can supply two loads simultaneously, one at 100 per cent

and the other at 50 per cent voltage. When the power factors of the two loads are approximately equal, the curve in Fig. 252*b* gives the kv.a. in each circuit (in per cent of the kv.a. rating of the transformer bank) that can be supplied simultaneously without overloading the transformers. When the power factors of the two circuits are widely different, the capacity of the bank for simultaneous loads may be reduced to 86 per cent of that given by the curve.

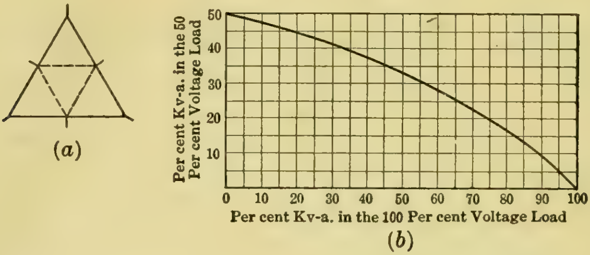


FIG. 252.—Simultaneous Loads on Full Winding of Secondary and 50 Per Cent Tap on Primary.

In some cases it is desired to have the 50 per cent tap in the primary winding. In Fig. 253 are given the combinations of simultaneous loads on the secondary and 50 per cent primary taps. The total load is greater than that given in Fig. 252 because the bank acts as an auto-transformer for one of its loads.

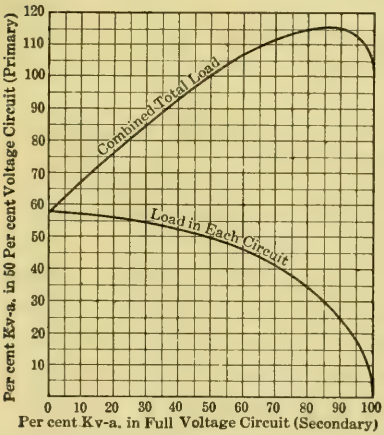


FIG. 253.—Simultaneous Loads on Full Winding of Secondary and 50 Per Cent Tap of Primary. (Primary Acting as Auto-transformer on its 50 Per Cent Tap.)

For delta-delta-connected transformers, the effect of different impedances is an unequal division of load among the three transformers. The curves of Fig. 254 show the relation of current in the three legs of the delta, assuming two legs to be alike in percentage impedance and capacity. The abscissae represent ratio of impedances of odd leg to the like legs.

$$r = \frac{Z_3}{Z_1} = \frac{Z_3}{Z_2},$$

where Z_1, Z_2 and Z_3 are the impedances of the different legs. But since Z is proportional to $\frac{\%IZ}{\text{kv.a.}}$, we can write

$$r=\frac{\left(\frac{\%IZ}{\text{kv.a.}}\right)_3}{\left(\frac{\%IZ}{\text{kv.a.}}\right)_1}=\frac{\left(\frac{\%IZ}{\text{kv.a.}}\right)_3}{\left(\frac{\%IZ}{\text{kv.a.}}\right)_2}.$$

If I_L = line current for any given balanced load, and I_1, I_2 and I_3 are

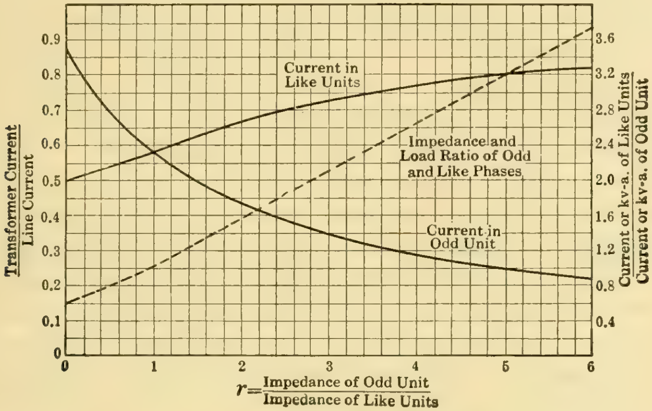


FIG. 254.

the leg currents, with the same load, the ordinates of the curve represent the ratio of leg current to line current $\frac{I_1}{I_L}=\frac{I_2}{I_L}$ and $\frac{I_3}{I_L}$ respectively.

If, for example, we have three transformers connected in delta-delta, with capacities and impedances as follows:

$$\text{kv.a.}_1=100; \qquad \text{per cent } IZ_1=2;$$
$$\text{kv.a.}_2=100; \qquad \text{per cent } IZ_2=2;$$
$$\text{kv.a.}_3=50; \qquad \text{per cent } IZ_3=2.3;$$
$$\text{line voltage}=1000;$$

we find that

$$r=\frac{2.3\div 50}{2\div 100}=2.3$$

and

$$\frac{I_1}{I_L}=\frac{I_2}{I_L}=0.68;$$

also

$$\frac{I_3}{I_L}=0.40.$$

If $I_1=100$ amperes, the normal current for that transformer,

$$I_L=\frac{100}{0.68}=147 \text{ amperes.}$$

I_3 would then be equal to $147\times0.40=59$ amp. or 18 per cent overload on leg 3.

Again, if we assume that $I_3=50$ so as not to overload leg 3, $I_L=125$ and $I_1=85$, and legs 1 and 2 are, therefore, carrying only 85 per cent of their rated capacity. This means that without any overload on any of the three transformers, the system can carry only 125 amp. line current or 87 per cent of the rated capacity of the three transformers.

At the point where $r=\infty$, we have the current in legs 1 and 2 equal to the line current, giving the condition of open delta. By decreasing the capacity of leg 3 to zero, which is the same as increasing its impedance to infinity, we have the case of open-delta.

In a delta-delta bank consisting of two similar and one odd units, maximum output is obtained only when the different phases divide the load directly as their rated kv.a. capacities. The impedance ratio which will make the load division in this desired manner can be determined very conveniently by the aid of Fig. 254, which is used as follows: First determine the ratio of the kv.a. rating of one of the two similar phases to that of the odd phase. With the aid of the dotted curve in Fig. 254 determine the impedance ratio which will give this ratio of load division. For instance, consider again the foregoing example. The ratio of the kv.a. rating of one of the like units to that of the odd unit is 100/50 or 2. Find 2 on the right hand vertical scale and locate it on the curve of current ratios. Reading the abscissa corresponding to this point we find the impedance ratio (Odd unit/Like units) to be 2.85. That is, the per cent impedance of the 50 kv.a. transformer should be 2.85 times the per cent impedance of the 100 kv.a. transformers. This impedance ratio is of course to be based on the same kv.a. load basis. Using the 50 kv.a. rating as basis, the impedance of the like units is 1 per cent. Multiplying this by 2.85, we get 2.85 per cent reactance necessary for the 50 kv.a. unit. The actual impedance of the odd unit is 2.3 per cent. This can be increased to 2.85 per cent by connecting a 0.55 per cent reactance in series with it. The kv.a. rating of this series reactor will be 0.55 per cent of 50 kv.a. or just 0.28 kv.a. which is quite small. Without this series reactance the bank can deliver 216 kv.a. without overloading the 50 kv.a. unit. With this reactor connected in, the bank can deliver about 243 kv.a. Thus, there is a gain of 27 kv.a. in the capacity of the bank by adding to it a 0.28 kv.a. reactor.

If the per cent impedance and kv.a. capacities of all three of the phases are dissimilar, the load division may be calculated as follows:

Let (per cent kv.a.)$_1$ denote the load in phase No. 1 in per cent of the total load on the lines, (per cent kv.a.)$_2$ the load in phase No. 2 in per cent of the total load on the lines, and similarly (kv.a.)$_3$ the load in phase No. 3.

Then

(Per cent kv.a.)$_1$ =

$$50\sqrt{\frac{(R_2+R_3\pm 0.58X_2\mp 0.58X_3)^2+(X_2+X_3\mp 0.58R_2\pm 0.58R_3)^2}{(R_1+R_2+R_3)^2+(X_1+X_2+X_3)^2}}.$$

(Per cent kv.a.)$_2$ =

$$50\sqrt{\frac{(R_3+R_1\pm 0.58X_3\mp 0.58X_1)^2+(X_3+X_1\mp 0.58R_3\pm 0.58R_1)^2}{(R_1+R_1+R_3)^2+(X_1+X_2+X_3)^2}};$$

(Per cent kv.a.)$_3$ =

$$50\sqrt{\frac{(R_1+R_2\pm 0.58X_1\mp 0.58X_2)^2+(X_1+X_2\mp 0.58R_1\pm 0.58R_2)^2}{(R_1+R_2+R_3)^2+(X_1+X_2+X_3)^2}}.$$

In these formulae,

1. R_1, R_2, R_3, X_1, X_2, X_3 are the resistance and reactance ohms of the respective phases. If the rated capacities of the three phases are alike, then, (per cent IR)$_1$ may be substituted instead of R_1, (per cent IX)$_1$ instead of X_1, etc. If the rated kv.a. capacities are also dissimilar, substitution may be made as follows:

$$\text{For } R_1 \text{ substitute } \frac{(\text{Per cent } IR)_1}{(\text{Rated kv.a.})_1}.$$

$$\text{For } X_1 \text{ substitute } \frac{(\text{Per cent } IX)_1}{(\text{Rated kv.a.})_1}.$$

$$\text{For } R_2 \text{ substitute } \frac{(\text{Per cent } IR)_2}{(\text{Rated kv.a.})_2}.$$

$$\text{For } X_2 \text{ substitute } \frac{(\text{Per cent } IX)_2}{(\text{Rated kv.a.})_2},$$

etc. That is, resistances and reactances which are substituted in these formulae must all be based on the same load.

2. The upper algebraic signs in these formulae refer to one phase-rotation, the lower signs to the opposite phase rotation. Load division and maximum capacity of bank are thus dependent also on phase rotation.

3. Maximum output or capacity of the bank is calculated by determining that line kv.a. will load a given phase fully. This being calculated for each phase, the minimum of the three line kv.a. so calculated represents maximum capacity of the bank without overloading any phase. Thus, to fully load the indicated phase, the load on the lines will be,

$$\text{Line kv.a.} = \frac{100\ (\text{Rated kv.a.})_1}{(\text{Per cent kv.a.})_1}.$$

or

$$= \frac{100\ (\text{Rated kv.a.})_2}{(\text{Per cent kv.a.})_2},$$

or

$$= \frac{100\ (\text{Rated kv.a.})_3}{(\text{Per cent kv.a.})_3}.$$

4. It will further be noticed that these formulae also apply when

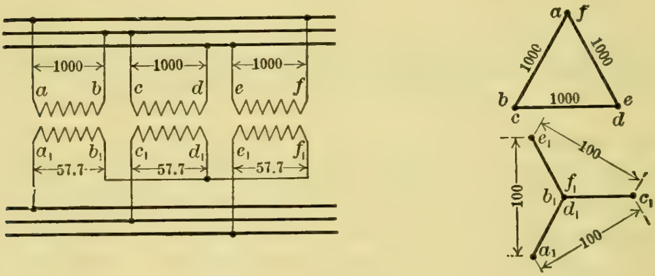


FIG. 255.

two of the phases are alike, also when all three phases are alike. In the latter case the formulae reduce to,

(per cent kv.a.)$_1$ = 33.3.

(per cent kv.a.)$_2$ = 33.3.

(per cent kv.a.)$_3$ = 33.3

That is, each phase carries 33.3 per cent or one-third of the line kv.a., which evidently is true.

5. Load division is independent of the load power factor, provided the power factor is the same on each phase.

Delta-Y. Delta-Y connection or vice versa, as shown in Fig. 255, is used to a great extent, and it is especially convenient and economical in distributing systems, in that a fourth wire may be led from the neutral point of the low-voltage windings.

The current and voltage relations in the delta side are the same as in the delta-delta connection. On the Y-connected side, however,

one end of each winding is connected to a common neutral point and the other three ends to the lines. With this connection the number of turns in a transformer winding is 58 per cent of that required for delta-connected transformers, but the cross-section of the conductors must be correspondingly greater for the same output.

Although the induced voltage in each phase of a Y-connected bank of transformers is less than the induced voltage in a delta bank designed for the same line voltage, nevertheless, they are designed with the same insulation strength to ground. This is due to the fact that abnormal insulation stresses are largely a function of the line voltage. Moreover, in accordance with the A.I.E.E. Rules, high potential tests are based on "the normal voltage of the circuit to which the apparatus is connected."

It is now generally conceded that in high-voltage power systems,

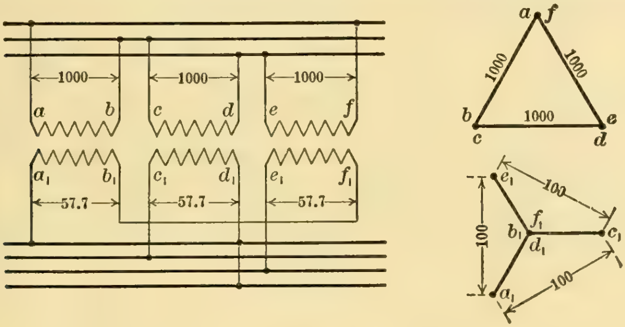


FIG. 256.

if the neutral of the system is solidly grounded, the insulation stresses are considerably reduced, and for that reason is should be safe to reduce the insulation of transformers designed for operation on such systems, provided that the neutral of these transformers also is solidly grounded. However, as many factors affect the insulation stresses to which transformers are subjected in service, it is not advisable to give a general rule. Each case should be given careful engineering consideration in order to be sure that the insulation may be safely reduced without endangering the apparatus.

For distributing service, as previously stated, the transformers often have their low-voltage windings Y-connected and the neutral brought out, forming a four-wire system, as shown in Fig. 256. The single-phase service is then obtained by tapping between any line and the neutral, while for three-phase work the line wires are tapped directly, the voltage between these being $\sqrt{3}$ times the single-phase. This

system results in a copper saving of 56 per cent, assuming that the four wires are of the same cross-section.

Transformers are sometimes designed so as to be suitable for either delta-delta or delta-Y connection, in order to permit the user to increase the capacity of a transmission line by raising the line voltage, which can be accomplished by changing the connection from delta to Y on the high-voltage side. Such transformers are necessarily more expensive than they would be if designed for straight delta-delta, and used at the lower voltage only, because they must be insulated to withstand the higher line voltage.

The rating of a group of delta-Y-connected transformers is the same as for the straight delta-delta connection.

Where power is transmitted with delta-Y step-up and Y-delta step-down transformers on a solidly grounded system, service may be maintained at reduced load with a transformer cut out from either the

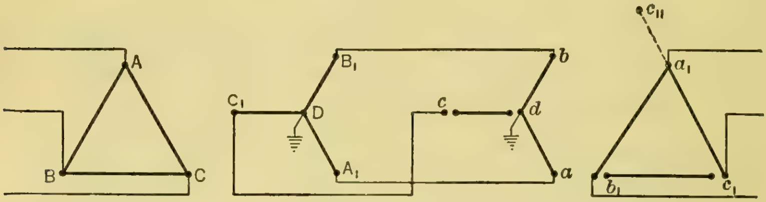


Fig. 257.

step-up or the step-down bank, or both. When a transformer is cut out from each one of the two banks, they must be cut out from the same phase. Thus, referring to Fig. 257, A_1, B_1, C_1 represent the Y-connected high-voltage winding of the step-up transformers, and a, b, c represent the high-voltage winding of the step-down transformers, the transformer cd being disconnected. Both the step-up and the step-down banks are operating in open-delta with the remaining units.

The capacity of the bank in such open-delta operation is only 58 per cent of that of the original closed-delta bank; therefore, such operation is used only as an emergency measure due to the failure of a transformer in one of the banks. In connecting up for such service, care must be taken to obtain correct phase relation between primary and secondary, e.g., not to connect a_1 c_1 in the position a_1 c_{11}.

The connection between the two neutrals should preferably be made through a wire, but can be made by solidly grounding the neutral of both transformers. The system will, however, be electrostatically and electromagnetically unbalanced, and the usual disturbances

characteristic of such a condition will be observed, the severity depending on the circuit characteristics. Furthermore, considerable telephone interference may also result from such operation.

Synchronous converters are frequently installed in connection with Edison systems, where three-wire direct current is required. Three-wire feature is readily obtained by connecting the neutral wire directly to the neutral point of the low-voltage winding of the step-down transformers. Care should be taken, in such a case, to use only such connections that the transformer will act non-inductively for the direct current, that is, that the direct current in each transformer divides into two branches of equal and opposite M.M.F's. If this is not done, the direct current will produce a unidirectional magnetism in the transformer, which, superimposed on the magnetic cycle, would tend to raise the magnetic induction beyond saturation, and thus cause excessive exciting current and heating, except where the unbalanced current is comparatively small. Such a connection is shown in Fig. 258 which

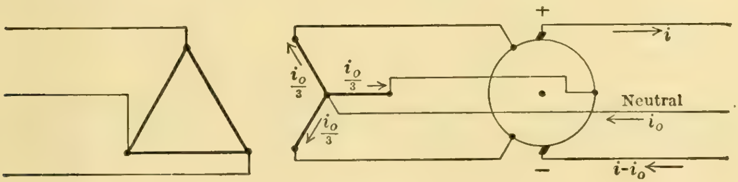


FIG. 258.

represents a delta-Y-connected step-down transformer with the neutral brought out. It is evident that in this case each transformer low-voltage winding receives one-third of the neutral current, and if this current is not small, as compared with the exciting current of the transformer, it will cause an increase in the magnetic density.

A system with a distributed Y or "zig-zag" connected low-voltage winding, as shown in Fig. 259, has, however, been devised, and will eliminate the flux distortion due to the unbalanced direct current in the neutral. Two separate interconnected windings are used for each leg of the Y. The unbalanced neutral current flowing in this system may be compared in action to the effect of a magnetizing current in a transformer. The effect of the main transformer currents in the high- and low-voltage windings is balanced with regard to the flux in the transformer core, which depends upon the magnetizing current. When a direct-current is passed through the transformer, unless the fluxes produced by the same neutralize one another, its effect on the transformer iron varies as the magnetizing current. For example, assume

a transformer having a normal ampere capacity of 100 and, approximately, six amperes magnetizing current, and assume that three such transformers are used with Y-connected low-voltage windings for operating a synchronous converter connected to a three-wire Edison system. Allowing 25 per cent unbalancing, the current will divide equally among the three legs giving 8.33 ampéres per leg, which is more than the normal magnetizing current. The loss due to this current is, however, inappreciable, but the increased core losses may be considerable. If a distributed winding is used the direct current flows in the

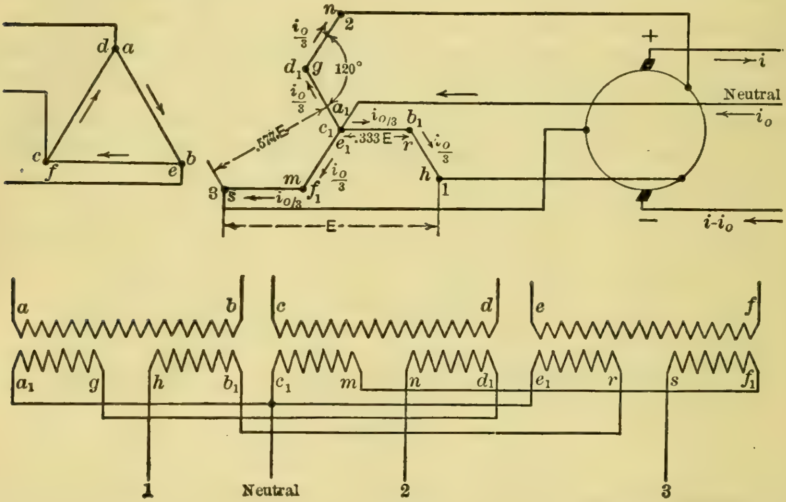


FIG. 259.

opposite direction around the two halves of each core, thus entirely neutralizing the flux distortion.

Whether the straight Y or the interconnected Y connection is to be used is merely a question of balancing the increased core loss of the straight Y connection against the increased copper loss and the greater cost of the interconnected Y system. The straight Y connection is much simpler, and it would be quite permissible to use it for transformers of small capacities where the direct current circulating in the neutral is less than 30 per cent (10 per cent per transformer) of the rated transformer current.

When three-phase core-type transformers are used, it is not necessary to resort to the zig-zag connection, as in such transformers the direct current flows along the core from end to end in the same direction on all three legs, and since the direct magnetism must find its return

path through the air and the case outside of the core, its affects are practically negligible.

On account of the 30° displacement between the voltage from line to neutral and that across each half of the transformer legs of the zig-zag connected windings, the low-voltage side operates only at 86.6

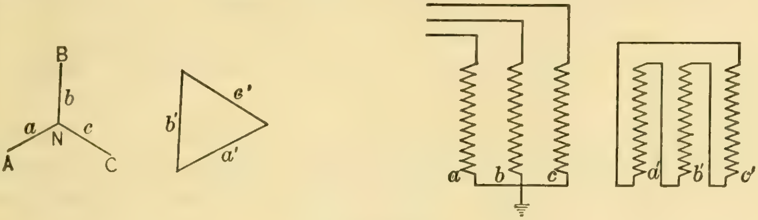


Fig. 260.

per cent of the normal capacity, which it would have if operated straight Y.

In delta-Y connection, unlike the delta-delta connection, differences in the ratio and impedance of the various units affect only the magnetizing current and do not appreciably alter the division of load; neither do they cause any appreciable currents to circulate.

In delta-Y connection, any circulating current in the delta acts as a

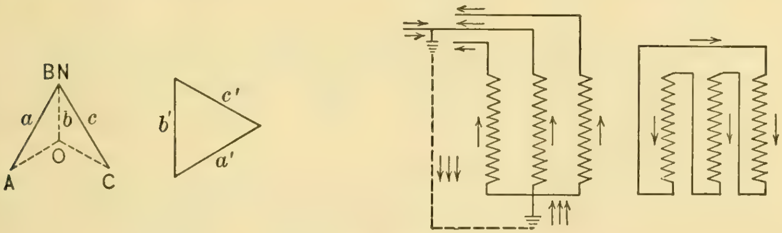


Fig. 261.

magnetizing current, because it can have no equivalent on the Y side. Its heating effect is negligible.

In the Y-delta bank with neutral grounded (Fig. 260), a ground on any line on the Y side produces short-circuit currents in all three legs (in both primary and secondary coils) and a voltage distortion as shown in Fig. 261. The short-circuit currents are:

$$I_S = \frac{100 \times I}{\text{Per cent } IZ'}$$

Where I = rated load current, and

Per cent IZ = per cent impedance per leg for the rated current.

The current in the short circuit equals $3I_S$, that in one of the lines $2I_S$, and that in the other lines I_S, as shown. *BO* is reactance drop between primary and secondary windings.

If the voltage is maintained on the primary lines, the secondary load voltages remain unaltered by the short circuit.

Frequently a question arises regarding the changing over of existing banks of transformers from delta to Y connection on the high-voltage side, for the purpose of increasing the line voltage to 1.73 times its former value.

If the transformer was designed for Y connection, the Y voltage is shown in the name-plate rating, and, of course, successful operation on that connection is guaranteed. If the Y voltage does not appear in the rating such connection should not be recommended even though the neutral point is to be solidly grounded.

The reason for this is as follows: The normal voltage stress to ground in Y connection is 73 per cent more than that in delta connection; and although the former is less than the test voltage which the transformer intended for delta connection has received, yet the continued operation of the transformer under a voltage stress 73 per cent higher than intended may shorten the useful life of the insulation. This is especially true for high-voltage transformers. An exception to the rule is the case of certain distributing transformers up to 3000 volts high voltage, in which the insulation is designed with a much higher factor of safety than that of large power transformers. They, therefore may be connected in Y, and in such cases, in order that the stresses may be kept as low as possible, it is preferable to operate the system with its neutral solidly grounded.

Y-Y. Transformers operating in Y-Y connection, with the exception of the three-phase core-type units, have considerable third harmonic voltage induced in their windings, due to the suppression of the third harmonic component of the normal exciting current. At ordinary core densities, the third harmonic voltage is about 50 per cent and may be as high as, but not more than, 75 per cent of the fundamental. Its maximum approximately coincides with that of the fundamental and directly adds to the insulation stresses in each leg. When the neutral is isolated, the third harmonic voltage appears between neutral and ground, and the line is not affected; when the neutral is grounded it appears between lines and ground.

The third harmonic voltage is practically eliminated under the following conditions:

1. When a tertiary delta winding is provided.
2. When the primary neutral is connected to that of the generator.

3. When the neutral of either side (primary or secondary) is connected to the neutral of a Y-delta bank across the lines on the same side (primary or secondary).

4. When the secondary is diametrical and is connected to a rotary converter.

The position of the neutral in a Y-Y bank is determined largely by the following three factors:

Since it is practically impossible to obtain three transformers of exactly the same magnetizing current, it therefore is impossible to guarantee perfectly balanced leg voltages in a Y-Y bank. This is in marked contrast with the delta-Y connection, where the magnetizing currents adjust themselves so as to maintain balanced voltages, whereas in Y-Y connection the voltages adjust themselves so as to maintain balanced magnetizing currents. This is particularly true for single-phase units or three-phase shell-type units, but is only partially true in three-phase core-type units, in which the leg voltages are balanced very much better, because the fluxes in the three legs must also balance as well as the magnetizing currents.

Y-Y-connected transformers, excepting three-phase core-type units, are not capable of supplying an appreciable single-phase load from line to neutral without a serious shift in the position of the neutral, because the corresponding primary currents of such loads, flowing through the primaries of the unloaded phases, magnetize them. This statement does not apply to unbalanced loads from line to line, because the shift of neutral in such cases is only due to leakage reactance and is very small.

In grounded Y-Y high-voltage systems where the line charging current is comparable to the transformer magnetizing current, an unbalanced charging current on the lines, produced by an unbalanced electrostatic condition of the lines with respect to the neutral, may shift the neutral seriously and may even reverse the voltage on one leg and produce very excessive voltages on the other legs. Thus, the neutral of a Y-Y bank is very unstable.

The above statements are primarily true for Y-Y-connected single-phase units and shell-type three-phase units. Core-type units, however, because of the interlinking of the magnetic fluxes in the three legs may give tolerably good results under conditions of single-phase loads from line to neutral or unbalanced electrostatic charging currents.

Y-Y-Delta. Delta-connected tertiary windings may be used in Y-Y-connected transformers for any of the following purposes:

To protect the transformer and system from excessive third harmonic potentials;

To prevent telephone interference due to third harmonic currents in the lines to ground;

To stabilize the neutral of the fundamental frequency voltages;

To supply a load in addition to any of the above purposes;

To protect the transformer and system from excessive third harmonic potential stresses, low reactance between the major winding and the tertiary is not necessary. Therefore, the tertiary winding may be designed to carry only the third harmonic magnetizing current, and the reactance between the primary and the tertiary should then be high enough to limit to a safe value the circulating current that would be produced in the tertiary by a line-to-neutral short circuit. The neutral may either be grounded or isolated, but the tertiary winding is more necessary for grounded systems as in these there is a possibility of the third harmonic voltage being intensified by resonance with the line capacitance to ground.

A tertiary winding is not necessary for this purpose when a three-phase core-type unit is used.

Telephone interference for a given telephone parallel circuit is proportional to the ampere miles of ground current, which is only indirectly a function of the third harmonic residual voltages. Thus, it is possible that with a low impedance ground, a three-phase core-type transformer with a three per cent residual voltage will produce practically as much unbalanced ground current as a bank of single-phase transformers with a 50 per cent inherent third harmonic voltage.

A properly designed tertiary winding may, therefore, be essential in order to eliminate these disturbances, even in a three-phase core-type transformer. When a tertiary is used, the third harmonic ground current is not entirely eliminated but is divided between the tertiary and the primary winding, the division being dependent upon the reactance between tertiary and primary, the impedance of the ground, and the arrangement of the windings with respect to the core.

In general, to stabilize the neutral, low reactance between primary and tertiary windings is essential, the stability being inversely proportional to this reactance. The degree of stability required depends upon the purpose for which the neutral is to be used.

1. If the tertiary winding is intended to stabilize the neutral when a single-phase load is taken from the line to neutral or under conditions of unbalanced loads on a four-wire three-phase system, the load in each phase of the tertiary is equal to one-third of the single phase or unbalanced load, and at this load the reactance drop between primary and tertiary should not be excessive.

If the unbalanced load is only a small fraction of the transformer

rating, a three-phase core-type unit may be used without a tertiary winding, provided that the reactance drop is not excessive, as calculated by formulæ given in the section on "Y-Y connection."

2. If the tertiary winding is intended to hold a stable grounded neutral on an otherwise isolated system, then the reactance should be as low as possible and the tertiary winding should be capable of withstanding the short-circuit current which will be limited only by the impedance of the generating system if it is desired to limit the shifting of the neutral to a minimum. This requires a large capacity in the tertiary, practically equal to the total capacity of the step-up transformers.

If, however, the tertiary winding is only required so as to draw a sufficient short-circuit current to operate the circuit-breakers when one of the lines becomes grounded, higher-reactance and relatively smaller-capacity tertiary windings may then be used, in which case,

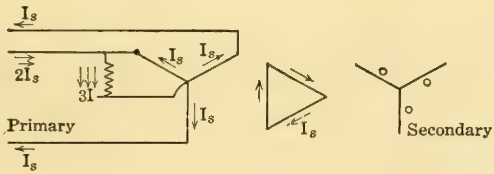


FIG. 262.

however, there will be considerable shift of neutral and also considerable rise of voltage on the lines with respect to ground.

If the ground and short circuit are on the excited side (see Fig. 262), the short-circuit current is equal to

$$I_S = \frac{100I}{\text{Per cent } IX_{PT}},$$

where I is the normal current, and per cent IX_{PT} is the impedance between primary and tertiary for it. The current in one line is twice I_S, whereas the current in each one of the other two lines is I_S.

If the ground and short circuit are on the secondary of the transformer (see Fig. 263), the short-circuit current in the tertiary is equal to

$$I_S = \frac{100I}{\text{Per cent } IX_{PS} + \text{per cent } IX_{PT}},$$

provided that the tertiary is not between primary and secondary

windings. If the tertiary is between primary and secondary windings, then

$$I_S=\frac{100I}{2\times\text{per cent } IX_{PS}+\frac{1}{3}\text{ per cent } IX_{TS}}.$$

In the above formulæ the subscript $_{PS}$ means between Primary and Secondary, $_{PT}$ means between Primary and Tertiary, and $_{TS}$ means between Tertiary and Secondary. The current in the short circuit is three times I_S (see Fig. 263), that in one phase of the primary is twice I_S, and that in each one of the other phases of the primary only I_S. It is to be understood that the value of I_S in the different coils must take into account the turn ratio, as all diagrams in this discussion assume a one-to-one turn ratio.

3. If the step-up transformers are isolated and the high voltage of the step-down transformers is grounded, a tertiary winding may be used

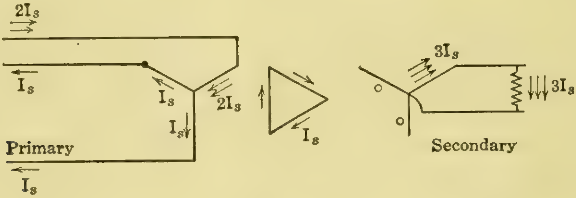


FIG. 263.

in the latter to permit a design for reduced test voltage. Under this condition, the neutral of the transformer should be solidly grounded, and the reactance between the high voltage and tertiary windings should not be more than the impedance of the system on the generator side of the step-down transformer.

4. If the neutral of the step-up transformers is solidly grounded, and if the neutral of the high-voltage winding of the step-down transformers is also grounded and the latter is equipped with a tertiary winding (see Fig. 264), the short-circuit current in the tertiary due to a line ground is equal to

$$I_S=\frac{100I}{3\times\text{per cent } IZ'}$$

which shows that the short-circuit current is one-third of what it would be if the step-up transformers were isolated. Therefore, the capacity of the tertiary need be only one-third in the former case, as in the latter, provided the tertiary is not supplying a load.

Tertiary windings intended for any of the above purposes are

sometimes made use of also to supply a load, frequently a condenser load for power-factor correction. In such cases, there is the possibility of a short circuit on the lines of the tertiary windings also. Hence, a tertiary winding intended to support a load must be so designed as to be able to withstand a short circuit on its own lines as well as short circuits on other windings.

In the following is given the various Y-Y connections in order of their preference:

Case 1: Three-phase core-type is to be preferred because, by virtue of the core structure the third harmonic, voltage is reduced to a negligible value. The neutral may be either grounded or isolated.

Case 2: All other types, provided the neutral is permanently connected to the generator neutral. As a solid, low-resistance connection to the generator neutral reduces the third harmonic to a negligible value, this connection is satisfactory.

Case 3: When transformer is equipped with tertiary delta winding.

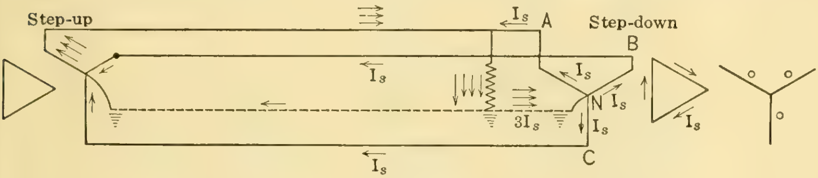


FIG. 264.

With a low-reactance tertiary delta, the operating characteristics are superior to cases 1 and 2, since the transformers then operate as a Y-delta transformer. However, the expense of providing tertiary delta solely for this purpose is generally prohibitive.

Case 4: Y-diametric connection for operating rotary converters. The connection with the armature of the rotary permits the circulation of third harmonic current and thus reduces the third harmonic voltage to a negligible value.

Case 5: Y-Y connection, in either of the above cases, when operating with neutral isolated, contains a 50 per cent third harmonic voltage, which adds to the insulation stress in the windings. When sufficient insulation is provided to care for this extra stress there is no objection to such operation, since the third harmonic voltage exists between neutral and ground and does not appear in the line.

Case 6: Y-Y connection with grounded neutral accompanied by a Y-delta or zigzag transformer bank, with grounded neutral to permit circulation of third harmonic current. This connection is effective in

reducing the third harmonic voltage to small values, but has the objection that in the event of disconnecting the Y-delta or zigzag bank the connection reduces to that of Case 7.

Case 7: Y-Y connection with grounded neutral. This connection is dangerous on account of the possibility of resonance in the third harmonic with the line capacitance, and therefore should never be used.

Open-delta. When single-phase or three-phase shell-type transformers are used, it is possible to maintain operation if one phase is damaged. Such a combination is shown in Fig. 265, and is termed the open-delta or V connection. With delta-connected shell-type transformers, to operate in open-delta when one phase becomes damaged, the damaged phase should be disconnected from the rest and short-circuited on itself to prevent the fluxes of other phases from

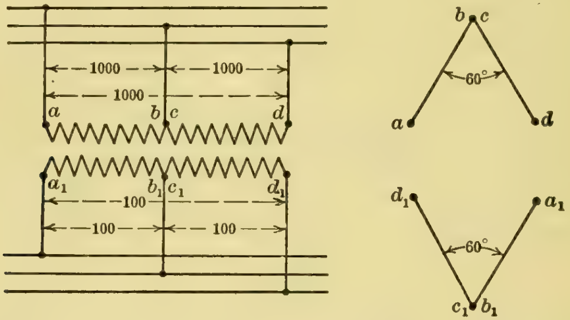


Fig. 265.

inducing voltage in the damaged winding. In the three-phase core-type transformer it is possible to operate open-delta, but only when the damaged winding is open-circuited and is capable of withstanding normal voltage.

With the V connection the current in each transformer is 30° out of phase with the transformer voltage, so that each transformer under non-inductive load operates at only 86.6 per cent power factor. Based on a three-phase load, the cutting out of one transformer would therefore reduce the current-carrying capacity not to two-thirds of 100 per cent, which equals 66.6 per cent, but to two-thirds of 86.6 per cent which equals 58 per cent.

Assuming that each transformer shall have a capacity of $\frac{3EI}{2} = 1.5EI$, it must be capable of carrying $1.73EI$ kilovolt-amperes, because the transformer voltage is equal to the line voltage E, and the transformer

current equal to the line current $1.73I$. Therefore, the single-phase rating of each transformer must be $\frac{1.73}{1.5} = 1.155$ or $15\frac{1}{2}$ per cent greater than one-half the group rating.

Parallel operation of open-delta banks with closed-delta banks is sometimes desirable in case of failure of a unit in one or more banks, or when it is desired to combine all available units for maximum possible output.

In general, the maximum output from a given number of similar single-phase units is obtained by forming as many closed-delta banks as possible. If two units are left over, an open-delta bank may profitably be added. If a single unit is left over, the practice of breaking up one of the closed deltas, so as to form two open deltas with the aid of the unit which is left over, may be recommended for cases No. 6 and No. 10 Table XLVI, but not for cases No. 7 and No. 9. It must be borne in mind that this tabulation is intended for identical units and does not apply if the kv.a. capacities or impedances of the units are unlike.

TABLE XLVI

Case	Number of Transformers	Connection	Three-phase Capacity of Group in per cent of Single-phase Rating
1	3	△	100
2	2	∧	86.6
3	2	⊤	86.6
4	6	△ △	100
5	5	△ ∧	80
6	4	∧ ∧	86.6
7	4	∧ ∠	82
8	9	△ △ △	100
9	7	△ ∧ ∠	91
10	7	△ ∧ ∧	78
11	8	△ △ ∧	88

The case of dissimilar units is best solved as follows: Parallel operation of open-delta banks with closed-delta banks, whether the units are similar or dissimilar, resolves itself into the case of a single delta of which the three branches consist of one or more (or zero) number of units, and each branch of the delta may then have a different kv.a. capacity and a different resultant impedance. A delta bank which has different kv.a. capacities and impedances in the three branches is already discussed on pages 396–400. In any combination of closed-

or open-delta banks, therefore, load division is most conveniently calculated by first calculating the kv.a. capacity and impedance of each phase as a single-phase bank, and, then with the aid of formulæ on page 399, determining the division of load.

In combining similar or dissimilar units for delta-delta operation, the guiding rule should be to make the kv.a. capacities and impedances of the three phases as nearly alike as possible.

Sometimes it is desired to parallel a number of transformers in such a way that certain of the transformers will form a delta group while the others may be connected in open-delta or V. Such a combination may be caused by the desire to increase the capacity by adding spare transformers of insufficient number to form a group of complete deltas, or through the failure of one or more units originally installed. It is not, however, generally realized that such an arrangement will, in general, prove either uneconomical as to capacity, if all the units are kept to rated currents, or disastrous to the units on the legs having the smaller numbers, if it be attempted to work all units at overloads guaranteed for single-phase operation. Not only is this likely to result from the additional $15\frac{1}{2}$ per cent capacity required on units for open-delta service, but a further increase in current takes place in the V-connected transformers, due to change in phase relation, and for this reason when delta and V groups are operated in parallel the resultant capacity is not the sum of the individual delta and V ratings. More than one V group cannot be used advantageously with a delta group of transformers nor with two or more paralleled delta groups. Three delta-connected transformers, when added to another delta group, will give more capacity than if four transformers, connected in two V groups, were added to the same delta group. This is because the four transformers, which would form two V groups, can be rearranged to form a delta group (one transformer remaining idle), and the delta group will have the capacity of three transformers, while the two V groups will add the capacity of only two transformers. The addition of two transformers, connected in V, in parallel with a delta group adds the capacity of only one transformer to the capacity of the total group. Although two V-connected groups should never be used in parallel with a delta group, they may be paralleled with one another and in this case will give a greater capacity than three units connected in delta. The capacity of the two V groups would be 0.866 times four or 3.46 as against three, the corresponding rating of three transformers connected in delta.

Table XLVI gives the transformer capacities available with various combinations of open- and closed-delta groups.

The regulation of an open-delta bank for a balanced three-phase load

is different for the different phases, and may be calculated approximately as follows. Formulæ:

Phase I. Per cent reg. = P. F. (0.86 × per cent IR + 0.50 × per cent IX)
+ R. F. (0.86 × per cent IX − 0.50 × per cent IR)

Phase II. Per cent reg. = P. F. (0.86 × per cent IR − 0.50 × per cent IX)
+ R. F. (0.86 × per cent IX + 0.50 × per cent IR)

Phase III. Per cent reg. = P. F. (1.73 × per cent IR) +
R. F. (1.73 × per cent IX)

Phase III is the open phase.

The reactances and resistances are per phase at their rated single-phase load. The balanced three-phase load for which the above regulation is figured equals 86 per cent of the rated kv a. of the two units.

The corresponding values of power factor (P. F.) and reactive factor (R. F.) are tabulated below:

Power Factor.	Reactive Factor.
1.00	0.00
0.95	0.32
0.90	0.44
0.85	0.53
0.80	0.60
0.75	0.66
0.70	0.71
0.50	0.87
0.00	1.00

T-T. As with the open-delta arrangement, the T-T connection requires only two single-phase transformers, Fig. 266, representing the diagram of connections. *A* is called the main transformer and is provided with a 50 per cent voltage tap to which the teaser transformer *B* is connected. This transformer may be designed for only 86.6 per cent of the line or main transformer voltage, but generally it is made identical with the main transformer and operated at reduced flux density. It should be noted that, although the teaser operates at 86.6 per cent of line voltage, it is not necessary, as is often supposed, to provide an 86.6 per cent tap. On this account it is possible to operate two identical transformers connected T-T as well as open delta, when one transformer of a delta-delta bank burns out, the only requirement for the T-T connection being a 50 per cent tap. Although interlacing is not required between halves of the main winding, nevertheless each half of the primary winding must be properly wound with respect to the corresponding half of the secondary winding. The three-phase

capacity of the T connection, as is shown in the table, is the same as for the open-delta connection, that is, 86.6 per cent of single-phase capacity; but on account of the fact that the teaser operates at a lower flux density, the efficiency of the T connection is somewhat greater than in the open-delta or V connection.

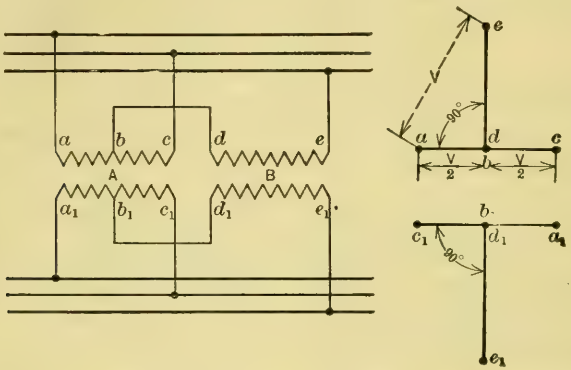


FIG. 266.

The T connection, as shown in Fig. 267, can also be used for three-phase synchronous converters, and the neutral point can readily be brought out for Edison three-wire service. The neutral is then brought out from a point at one-third the height of the teaser winding, and the M.M.F. of the direct current i will balance, as shown in the diagram.

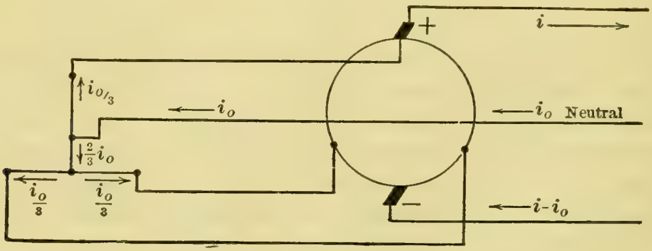


FIG. 267.

For T connection with ungrounded neutral, the voltage stress is the same as for the delta system, and with grounded neutral the voltage stress between line and ground is limited to 58 per cent of normal.

Assuming again that, as with the open-delta connection, the two transformers shall be capable of supplying a load equal to $\frac{3EI}{2}=1.5EI$, the kv.a. rating of the main transformer must, therefore, be equal to

$1.73EI$, while the kv.a. of the teaser transformer only is equal to $1.73I \times 0.866E = 1.5EI$. The two transformers are, however, designed to carry the same currents and are generally made identical, so that the single-phase ratings of either transformer must also here be $\frac{1.73}{1.5} = 1.155$ or 15.5 per cent greater than one-half the group rating.

Phase Transformation. Of the connections for transforming one polyphase system into another with a different number of phases, the following are the most commonly used:

Two- or three-phase to single-phase.
Two-phase to six-phase.
Three-phase to two-phase.
Three-phase to six-phase.

Two- or Three-phase to Single-phase.[1] It is practically impossible to transform from polyphase to single-phase by means of static transformation with balanced conditions. Various schemes have been proposed and investigated, but none of the combinations give better results than can be obtained by simply using a transformer across on phase.

The reason for this is explained by Dr. Steinmetz (A.I.E.E., 1892) to be as follows:

" Single-phase power changes from a maximum to zero and back to maximum every half cycle, while polyphase power is delivered at a constant rate. Therefore, any system capable of transforming from balanced polyphase current to single-phase current must be capable of storing energy during the interval of time when the power delivered to the single-phase side is less than the power received from the three-phase side. The transformer is incapable of fulfilling this requirement."

Nevertheless, it is desirable to know the best method of taking single-phase power from a three-phase system, and often ingenious although complicated connections are proposed with the idea of more uniformly distributing a single-phase load. Most of these schemes do not present a single feature that is superior to the placing of the single-phase load directly across two wires. When there is one feature which is apparently superior, there are generally undesirable features which more than offset it. The four schemes shown in Fig. 268, are ones commonly suggested and Table XLVII gives the characteristics of these connections and shows that they are inferior to straight single-phase transformation. All values, except for power, are given with

[1] Three papers on Single-phase Power Service from Polyphase Systems appeared in A.I.E.E. Proceedings for October, 1916.

reference to straight single-phase as unity. The total value of power delivered is the same in all cases. By straight single-phase is meant

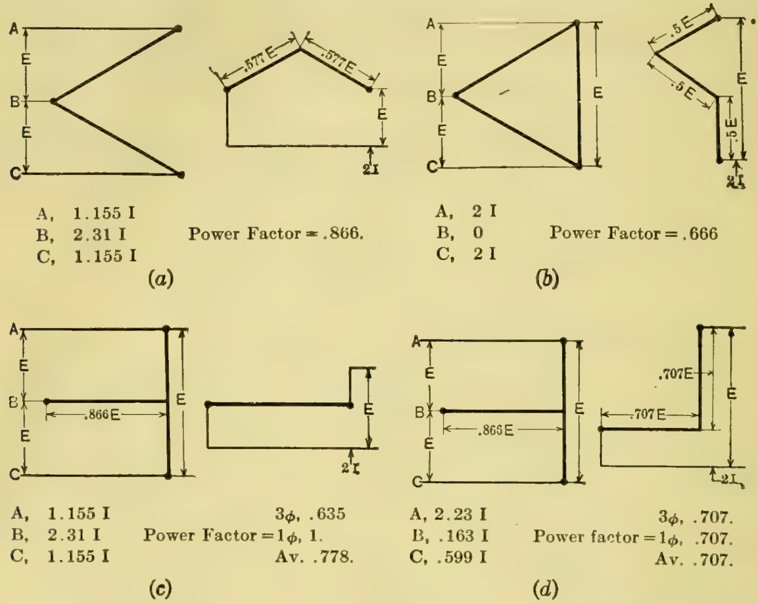


FIG. 268.

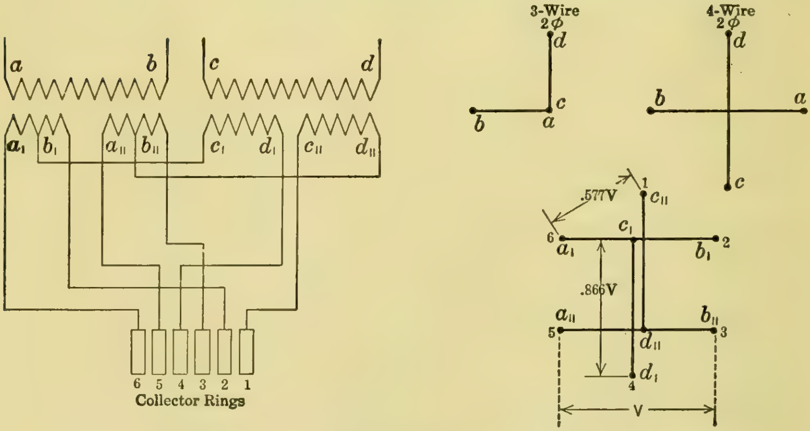


FIG. 269.

connecting one transformer between two wires of a three-phase system. The only condition under which there seems to be an advantage is in schemes 1 and 3 where it will be noticed that a delta-connected generator

has a maximum current of 0.577 as against 0.667 for the straight single-phase. To offset this, both schemes 1 and 3 require two transformers possessing greater total capacity, and also impose upon the line a greater maximum current.

TABLE XLVII

Scheme No.	No. Trans.	Capacity. Trans. Each.	Capacity. Cap. Total.	Power Factor for Non-inductive Load.	Generators. Y-connected. Current.	Generators. Y-connected. Watts.	Generators. Delta-connected. Current.	Generators. Delta-connected. Watts.
1	2	0.577	1.155	0.866	0.577	$\frac{1}{6}$	0.577	$\frac{1}{2}$
					1.155	$\frac{2}{3}$	0	0
					0.577	$\frac{1}{6}$	0.577	$\frac{1}{2}$
2	3	0.500	1.500	0.666	1.0	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{6}$
					0	0	$\frac{2}{3}$	$\frac{2}{3}$
					1.0	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{6}$
3	2 P	1.000						
		0.577		P 0.635	0.577	$\frac{1}{6}$	0.577	$\frac{1}{2}$
			1.577†		1.155	$\frac{2}{3}$	0	0
				S 1.000				
		S1.000		Av. 0.817	0.577	$\frac{1}{6}$	0.577	$\frac{1}{2}$
		0						
		0.707						
4	2 P	0.557*						
		0.150*						
			1.821*†					
				P 0.707	1.115	0.622	0.644	0.622
				S 0.707	0.815	0.333	0.172	0.045
							0.471	0.333
	S	0.707						
		0.707		Av. 0.707	0.300	0.045		
Straight Single-phase	1	1.00	1.00	1.00	1.0	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{6}$
					0	0	$\frac{2}{3}$	$\frac{2}{3}$
					1.0	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{6}$

* One-half of main has capacity of 0.557; other half 0.150; total capacity computed on basis that both halves are alike and of large capacity.

† On basis of primary capacities when there is a difference between primary and secondary.

Two-phase to Six-phase. The double-T connection, as shown in Fig. 269, is generally used in cases where a six-phase synchronous converter is to be operated from a two-phase supply system. The cost

of double-T-connected transformers and a standard six-phase rotary converter will occasionally be less than that of two-phase transformers and a special two-phase converter. T connection, however, requires specially designed transformers, and the complication of starting taps and switches is a disadvantage.

The system requires two transformers of the same impedance, each equipped with two low-voltage windings, connected in such a way that they are displaced 180° from each other, thus producing the six-phase relation.

The voltages are the same as for the T-connected three-phase system, and each transformer must be 15 per cent greater than half of the power required for the rotary.

The neutral can also be brought out on the six-phase side, although this furthermore increases the complication of the connection.

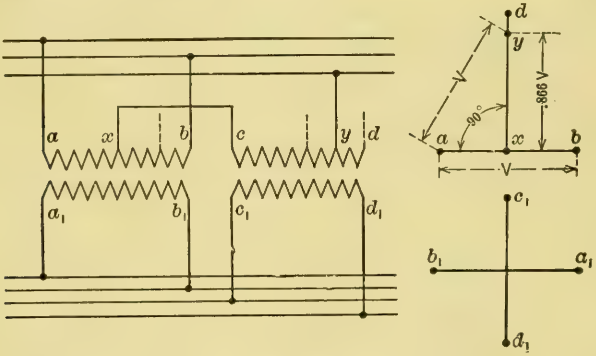


FIG. 270.

Three-phase to Two-phase. A number of schemes for three-phase to two-phase transformation, and vice versa, have been devised, but the most commonly used method is the Scott connection for either balanced or unbalanced service.

Balanced T or Scott Connection. This connection is shown in Fig. 270 and requires two transformers which on the three-phase side are connected in T, the number of effective turns in the teaser winding being 86.6 per cent of the number of turns in the main winding. On the two-phase side both mains and teaser windings are identical and, as shown in the figure, are electrically independent, when supplying a two-phase, four-wire system. Generally, the main and teaser transformers are made identical for the sake of interchangeability, in which case the three-phase winding is provided with both a 50 per cent and an 86.6 per cent tap, as shown by the dotted lines in Fig. 270, so that

when used as a main the 50 per cent tap is used and when used as a teaser the 86.6 per cent tap is used, the 13.4 per cent winding being left idle. Each of the two halves of the three-phase winding should furthermore be distributed over the entire winding length of the core in order to prevent flux distortion and poor regulation. The T connection requires 6.7 per cent more copper than single-phase transformers delivering the same power, on account of the idle copper in the teaser and also on account of the fact that wattless currents flow in the three-phase side of the main winding.

The neutral of the three-phase side, which is one-third the height of the teaser winding, can be brought out for four-wire operation, although the transformer construction is somewhat complicated thereby. When operating without the neutral point grounded on the three-phase side, the maximum insulation strain, if a permanent ground occurs, is equal to the line voltage V.

Unbalanced T. This connection may sometimes be of use in emergency conditions where a transformer with an 86.6 per cent tap is not available and a teaser transformer of the same voltage as the main transformer must be used.

In this connection two transformers of exactly the same capacity and voltage are used. When transforming from two-phase to three-phase with this connection, the three-phase voltages are not equal, and are not 120° apart; the voltages being as 1 : 1.12 : 1.12. When transforming from three-phase to two-phase, the two-phase voltages are in quadrature but are unbalanced in magnitude, having the ratio 1 : 1.15.

As this is not a true three-phase or two-phase system, any attempt to operate in multiple with a three-phase or two-phase system or synchronous apparatus will cause serious unbalanced currents.

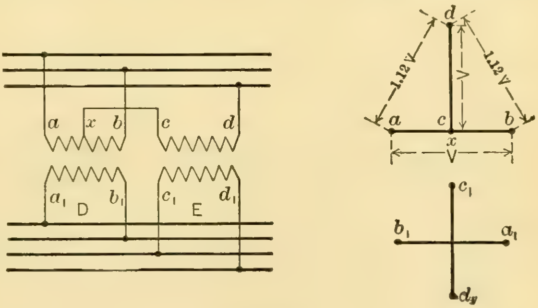


Fig. 271.

The connections and voltage relation of this system are shown in Fig. 271. With equal currents in the two-phase system, the currents in the three transmission wires will be the same as in the coils, namely: $a = 112$ amperes, $b = 112$, and $d = 100$, with the voltages as indicated in the diagram.

An unbalancing of the two-phase distributing network affects the currents in the three transmission wires, in that an increase of the load on phase *D* further increases the unbalancing, while, if phase *E* be loaded in the neighborhood of 15 per cent in excess of phase *D*, the transmission line currents become practically balanced.

With no neutral the maximum insulation stress under all conditions arising from a permanent ground would be 1.12 times *V*.

Symmetrical or Woodbridge Connection. In the previous two T-connected methods, the two-phase windings are electrically distinct. There are, however, a number of schemes in which the windings on the two-phase side are electrically interconnected in one way or another.

Such a system of connections is shown in Fig. 272. It consists of three windings, one for each phase. Two of the phases are identical,

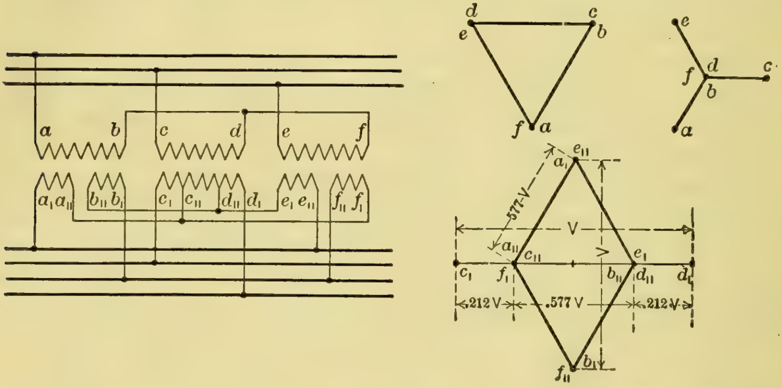


Fig. 272.

each consisting of two coils, wound for 0.577 times the two-phase line voltage and having a current capacity of 0.577 times the two-phase line current. The third phase consists of three coils, one being wound for 0.577 times the line voltage and the other two being identical and wound for 0.212 times the line voltage. The respective current capacities are 0.421, 1, and 1 times the line current.

One advantage of this system is the fact that voltages and currents do not exceed those which would occur in single-phase operation, giving an internal power factor of the system of 100 per cent, whereas in the T connections the average power factor is only 96.4 per cent. The three-phase side may be connected either delta or Y. This connection, requiring less copper and being slightly more efficient than the T connection, is recommended in place of the T connection for three-phase units, provided no taps are required on the two-phase side. If single-phase

units are desired, the use of this connection becomes doubtful owing to the multiplicity of leads and coils on the two-phase side. The connection is very seldom used, principally on account of the electrical interconnections of the phases on the two-phase side, which prevent it from being used on a three-wire system.

Three-phase to Three-phase—Two-phase. It is possible by means

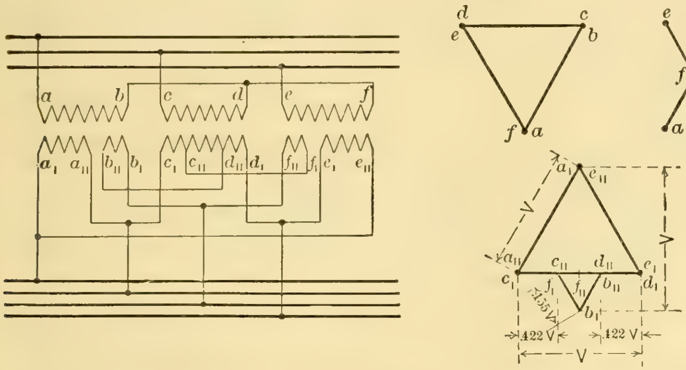


FIG. 273.

of transformer connection to derive from a three-phase primary circuit a four-wire secondary circuit, three wires of which represent a three-phase system while the four wires make a two-phase system. From such a system, independent three-phase or two-phase loads may be taken simultaneously. This may be accomplished by three single-phase transformers provided with special windings or by one three-phase transformer, as shown in Fig. 273. Primary winding may be connected either Y or delta and is in no wise different from an ordinary three-phase winding. The secondary, however, is provided with $15\frac{1}{2}$ per cent coils in two of the phases and $15\frac{1}{2}$ per cent taps in the other phase, which are interconnected in such a manner as shown in Fig. 273.

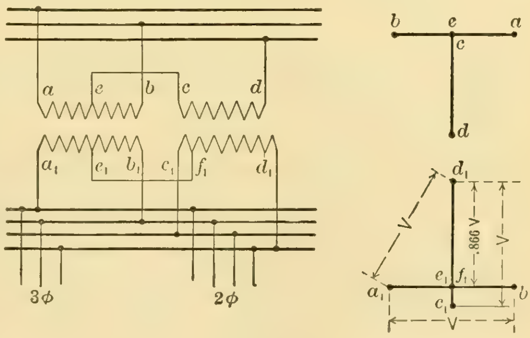


FIG. 274.

This may also be accomplished by means of two transformers T-connected, as shown in Fig. 274.

The choice between the two methods given above of obtaining three-phase and two-phase on four wires depends for the most part upon whether the three-phase or the two-phase load predominates. Where the three-phase load is predominant, it is evident that the connection given in Fig. 274 is superior; but where the two-phase load predominates, the T connection is preferable.

Three-phase to Six-phase. In transforming from three- to six-phase, there are four different connections which may be used, namely:

Diametrical.
Double-delta.
Double-Y.
Double-T.

These connections are used with synchronous converters. A correct understanding of the manner in which the winding of the latter is

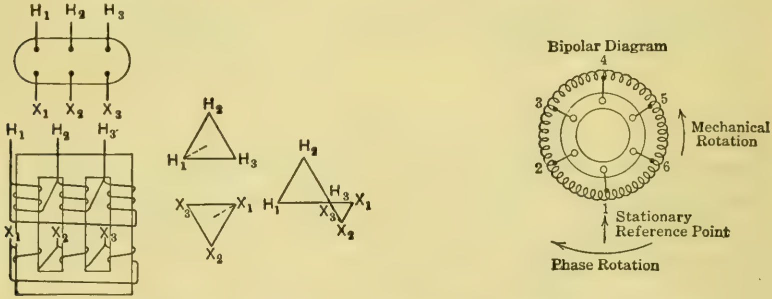


FIG. 275.—Phase Rotation in a Six-phase Synchronous Converter.

tapped and brought to slip rings, and of the system of numbering, is useful in understanding the method of connecting the transformer (or transformers) to the converter.

Figure 275 shows how the winding of a synchronous converter is tapped and brought to slip rings. The slip rings are numbered 1, 2, 3, etc., beginning from the bearing and proceeding towards the armature. The diagram also shows the actual direction of the physical rotation of the armature, which is counter-clockwise looking from the slip ring end of the machine. The actual electrical phase-rotation on the slip rings is clockwise, i.e., in the order 1, 2, 3, etc. Evidently the transformer must be so connected to the converter that neither the rotation of the latter is reversed nor any one phase is short-circuited. When the phase rotation on the high-voltage side of a polyphase unit is in the order H_1, H_2, H_3, the phase rotation on the low-voltage side is in the order X_1, X_2, X_3. Therefore, if the high-voltage supply phases are cor-

rectly connected to the high voltage of the transformer, then transformer and converter will operate properly when X_1 of the transformer is connected to ring 1 of the converter, X_2 of the transformer to ring 2 of the converter, etc. Although this is the standard connection, there are eleven others or altogether twelve operative connections which may be used if for any reason they are found more convenient. Of these twelve operative connections, six correspond to one phase rotation on the primary, and the other six to the opposite phase rotation on the primary. Thus, six of the possible connections for one-phase rotation are as follows:

Connect X_1 to Ring	1	or	2	or	3	or	4	or	5	or	6
X_2 to Ring	2	or	3	or	4	or	5	or	6	or	1
X_3 to Ring	3	or	4	or	5	or	6	or	1	or	2
X_4 to Ring	4	or	5	or	6	or	1	or	2	or	3
X_5 to Ring	5	or	6	or	1	or	2	or	3	or	4
X_6 to Ring	6	or	1	or	2	or	3	or	4	or	5

Each vertical row constitutes one operative set. Connections must not be made partially from one vertical row and partially from another. If on connection to power the converter rotates in the wrong direction, this should be corrected by reversing one phase on the high-voltage side.

Diametrical. The diametrical connection, as represented in Fig. 276, is the most commonly used of any three-phase to six-phase transformations, and there is very little reason for using any other connection for the operation of six-phase converters. It requires only one low-voltage coil on each transformer, and these coils are connected to diametrically opposite points on the armature windings. Furthermore, it gives the simplest arrangement of switches, transformer taps and connections for starting six-phase converters from the alternating current side, and it is possible to operate a six-phase converter at reduced capacity with one transformer out of service, leaving the other two connected across their respective diameters.

Single-phase units connected up for three-phase to six-phase transformation, may, like polyphase units, be connected to converters in twelve different ways, six with one-phase rotation on the primary and six with opposite phase rotation on the primary. Of these operative connections one simple case is shown in Fig. 276.

With diametrically connected low-voltage windings, the high-voltage windings should preferably be connected in delta so as to avoid the triple frequency harmonics of the E.M.F., as described under Y-Y connection on page 406. With regulating pole converters, however, the high-voltage windings must be connected Y on account of the

fact that the third harmonic voltage is made use of to obtain the direct-current voltage regulation, and in such a case the windings must be insulated for double line voltage to ground and 3.46 times normal Y-voltage across windings, owing to the presence of the third harmonic E.M.F's. The middle points of the diametrical windings can readily be connected together and brought out for three-wire Edison service, the unbalanced three-wire direct current having no distorting effect. Arrangements should then be made for opening the neutral connections during starting to avoid short circuit. When used with regulating pole converters, the neutral must be isolated.

The current in each coil on the low-voltage side is equal to $I = \frac{\text{output of transformer in watts}}{3 \times \text{diametral voltage}}$, assuming that the load is balanced and that the power factor is unity.

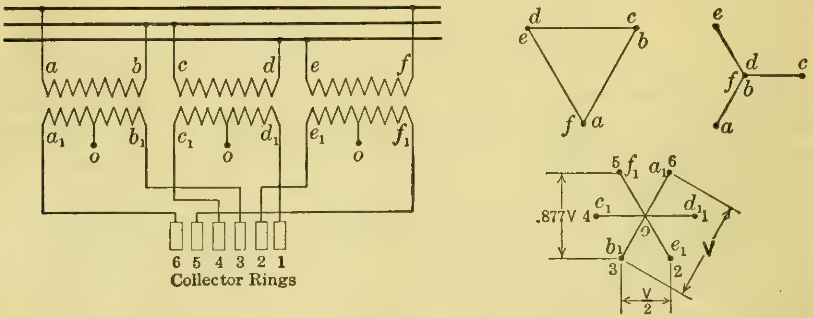


FIG. 276.

With six-phase diametrical connection with common neutral, one-half the output can be taken from the low-voltage side for operating three-phase without change of diametrical voltage. If full three-phase output should be desired, the coils can be connected in delta, in which case the diametrical voltage is increased 14 per cent. The full three-phase output at 1.73 times the diametrical voltage may be obtained by connecting the coils in Y, in which case the neutral should be grounded and if the high windings are Y-connected the system is subject to the dangers of the third harmonic E.M.F's., as previously explained. It must also be ascertained if the insulation of the windings can withstand the increased voltage safely. If the secondary windings are made up of two distinct sections, which is not, however, standard practice, the connections may be made as in Fig. 277. The latter connection is somewhat complicated, and when three-phase operation, with full output and without change of voltage is desired, the double-delta connection is generally preferable.

Double-delta. For the double-delta connection two independent low-voltage coils are required for each transformer, as shown in Fig. 278. The second set are all reversed, and then connected in a similar manner to the first set, so that the two deltas are displaced 180°.

The high-voltage windings should preferably be connected delta,

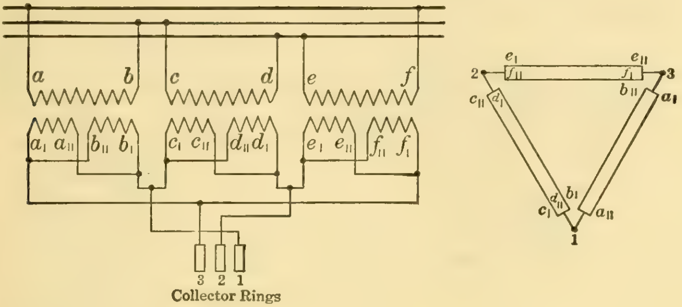


FIG. 277.

as this permits the system to be operated with only two transformers, in case one should be damaged.

The current in each coil for double-delta is equal to

$$I = \frac{\text{output in watts}}{\text{delta voltage} \times 2 \times 3}$$

and the current in each line equals $I \times 1.73$.

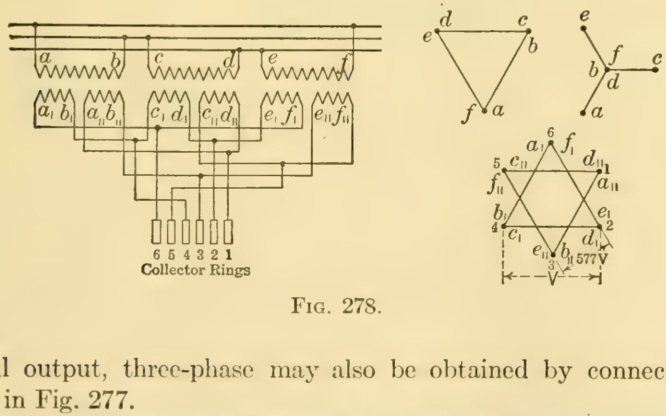


FIG. 278.

Full output, three-phase may also be obtained by connecting as shown in Fig. 277.

Double-delta connection cannot be used with Edison three-wire service, as it has no neutral, and in such cases separate auto transformers would be required.

Double-Y. Like the double-delta, this system requires two sets of low-voltage coils, displaced 180°, as shown in Fig. 279.

The high-voltage windings may be either delta- or Y-connected even with regulating pole converters, but in this case the two low-voltage neutrals must not be connected together. Where the high-

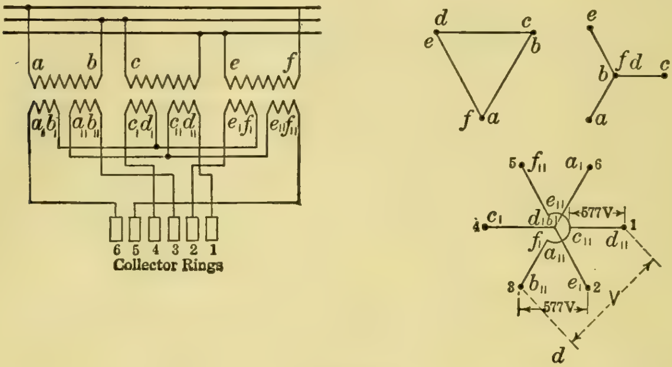


FIG. 279.

voltage windings are Y-connected, the danger of Y-Y operation should be considered, and the neutral should be grounded.

The current in each leg is equal to $I = \dfrac{\text{output in watts}}{\text{Y voltage} \times 1.73 \times 2}$ and the line current has the same value.

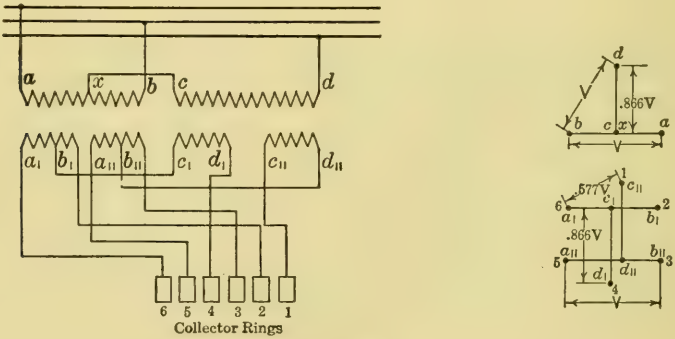


FIG. 280.

Double-T. Fig. 280 represents the double-T connection for transforming from three-phase to six-phase. The low-voltage connections are similar to the two-phase—six-phase system shown in Fig. 269, and the high-voltage windings are connected in T.

Figures 276 to 280 are the connections of single-phase transformers used for six-phase operation, and they do not apply to three-phase units. The vector diagrams, however, apply to both.

Parallel Operation. In order that two transformers of similar voltage rating may safely be connected in multiple, their polarity, phase rotation and angular displacement must be the same. Delta-delta and Y-Y transformers have correct angular displacement when

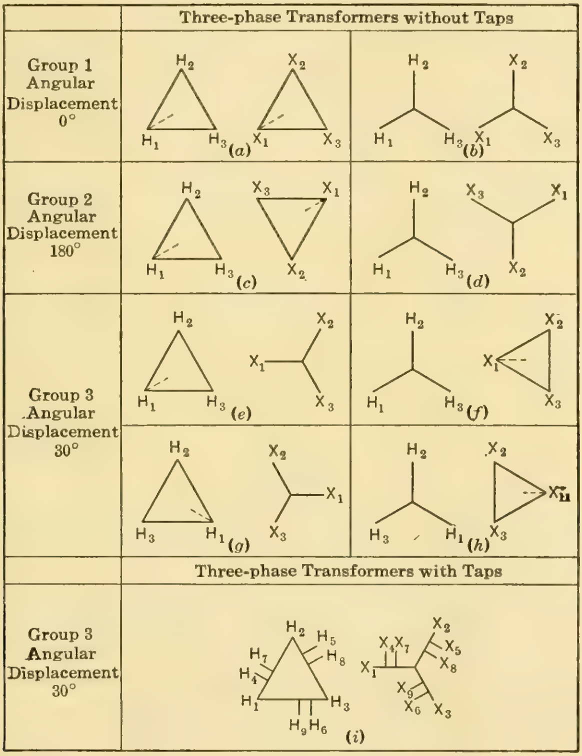


Fig. 281.

their polarity and phase rotation are correct. This however, is not necessarily true for delta-Y (or Y-delta) transformers. In this case, however, these can be adjusted by the proper selection of the sequence of leads.

If the voltage diagrams of the transformers which are to operate in parallel are available, it is then only necessary that these diagrams coincide, and corresponding terminals be connected together. It is entirely unnecessary then to raise questions of polarity and phase rota-

tion, because when the voltage diagrams coincide, leads which are to be connected together will have the same potential, this being the basic requirement for connecting in multiple, whereas, polarity, phase rotation, etc., are merely means to arrive at this condition. When voltage diagrams coincide, polarities and phase rotations must necessarily agree, although the converse of this is not necessarily true.

For the purpose of simplifying the connecting of transformers in parallel and avoiding the necessity of testing for polarity, phase rotation, etc., the A.I.E.E. and N.E.L.A. have standardized the marking of transformer leads covered in A.I.E.E. Rules. Transformers that are marked in this manner can be operated in multiple by simply connecting similarly lettered leads together. This, of course, is contingent on the transformers having proper characteristics, that is, ratio, impedance, angular displacement, etc.

Three-phase transformers are divided into three groups based on their angular displacements, as given in Fig. 281.

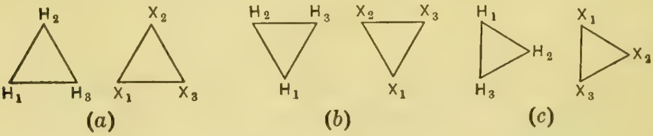


Fig. 282.

To operate in multiple, transformers must belong to the same group. No interchange of external leads can change one group into the other. Thus, two delta-delta transformers, one of group 1 and the other of group 2 cannot be operated in multiple. If the high-voltage diagrams be superposed, the low voltage diagrams will not coincide. All Y-delta or delta-Y transformers, however, can be reduced to the same diagram, and, therefore, they are classed in only one group. For instance, although on superficial inspection Fig. 281*g* seems to be different from Fig. 266*e*; yet, if one looks at the latter from the front of the page and the former through the back of the page, the two are exactly alike, and similarly lettered points coincide if the diagrams are superposed.

Confusion is sometimes experienced when voltage diagrams are shown in different positions, as for example in Figs. 282*a*, *b*, and *c*, where identically the same voltage diagram is shown in three different positions. What a voltage diagram indicates is not the actual potential of the terminals but the voltage vector relation between the two windings. This relation is identical in the above three figures. This can be seen still better if, for example, the high- and low-voltage diagram

of Fig. 282*b* is rotated clockwise through 60°, when it becomes identical with Fig. 282*a*. The same refers to Fig. 282*c* which would have to be rotated counter-clockwise through 90°.

Three-phase transformer banks will not operate in parallel unless the angular displacements between high and low voltages are equal. The operative parallel connections are as follows:

TABLE XLVIII

Operative Parallel Connections

	Low-Voltage Side.		High-Voltage Side.	
	A	*B*	*A*	*B*
1	Delta	Delta	Delta	Delta
2	Y	Y	Y	Y
3	Delta	Y	Delta	Y
4	Y	Delta	Y	Delta
5	Delta	Delta	Y	Y
6	Delta	Y	Y	Delta
7	Y	Y	Delta	Delta
8	Y	Delta	Delta	Y

There are four other combinations possible for these two banks of transformers, but these combinations will not operate in parallel. These are as follows:

TABLE XLIX

Inoperative Parallel Connections

	Low-Voltage Side.		High-Voltage Side.	
	A	*B*	*A*	*B*
1	Delta	Delta	Delta	Y
2	Delta	Delta	Y	Delta
3	Y	Y	Delta	Y
4	Y	Y	Y	Delta

Four of the usual three-phase to six-phase diagrams are shown above in groups 4 and 5, Fig. 283. Their construction involves nothing more complicated than the method indicated for three-phase. In these, the number of secondary leads being greater, the value of volt-

age diagrams is better appreciated, as may be illustrated by an example in which the leads are arbitrarily and irregularly marked as in Fig. 284*a* and *b*.

It is evident on inspection that both of them belong to the same

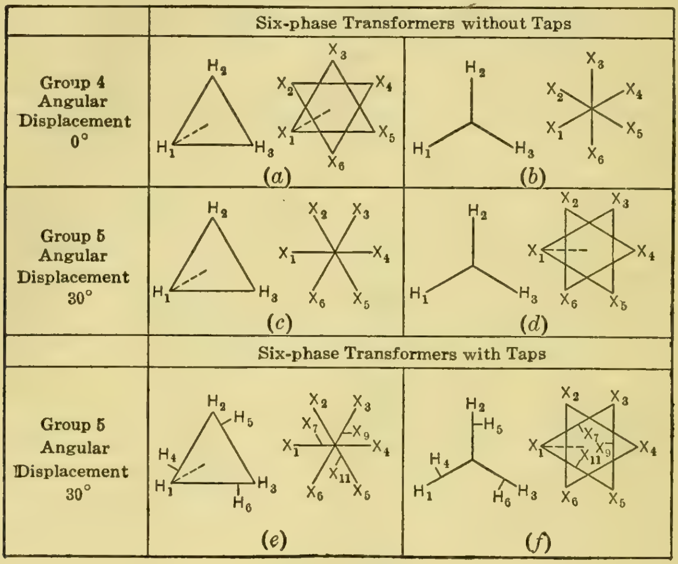


Fig. 283.

group (group 5 above), and the two may be paralleled by connecting their leads as follows:

A to 2; B to 1; C to 3;
E to 6; D to 5; F to 7; G to 8; I to 9; H to 10.

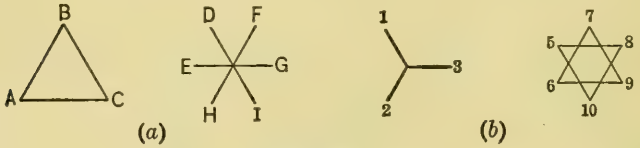


Fig. 284.

If this is not evident, it may be made so by assuming Fig. 284*b* to be revolved until 1, 2, 3 will coincide with A, B, C, respectively; then, the corresponding leads on the six-phase sides will be evident.

The above are not the only pairs of leads that can be connected together for paralleling. Two other combinations are also possible. In each case, rotate one of the diagrams (keeping the angle between

H.V. and L.V. the same) until desired leads on the three-phase side coincide; then the corresponding six-phase leads also coincide.

The connection of a six-phase secondary to a synchronous converter is similarly accomplished when their vector diagrams are given.

It may be of interest to note that the two delta windings of a double-delta secondary are necessarily of opposite polarity.

Effect of Ratio on Parallel Operation. For successful parallel operation, correct ratios between the high- and low-voltage windings of the different banks is, as previously mentioned, also essential; otherwise a cross-current will be established, even if the ratios are only slightly different. This current is then due to the difference of the two voltages divided by the sum of the impedances of the two transformers, and its effect is to balance the voltages of the two transformers with a resultant equilibrium of the two transformers.

To determine this current, assume that e_1 and z_1 are the voltage and impedance in low-voltage terms of one transformer and e_2 and z_2 are corresponding terms of the second transformer, connected in parallel with the other. The circulating current would then be

$$i=\frac{e_1-e_2}{z_1+z_2},$$

where z_1 and z_2 are expressed in ohms. Or expressed in percentage of normal current by the following formula:

$$\text{Per cent } I=\frac{\text{Per cent voltage difference}}{\text{Sum of per cent impedance}}\times 100.$$

For example, suppose that the voltage ratios of two transformers are such as to cause a voltage difference of 2 per cent. If each transformer, furthermore, has a 2 per cent impedance, the circulating current is equal to

$$\text{Per cent } I=\frac{2}{2+2}\times 100=50 \text{ per cent},$$

which means that a current equal to 50 per cent of normal circulates between the transformers in both high- and low-voltage windings. It adds to the load current in the transformer having the higher induced voltage and subtracts in the other, causing the former to carry the greater load.

The impedance Z_1 can be found for the first transformer by impressing a voltage on the low-voltage winding with the high-voltage winding short circuited. The current is then read, and if I is the current and E the voltage, then $z_1=\frac{E}{I}$. In the same manner z_2 is determined.

With three-phase delta-delta connected transformers, different voltage ratios will cause unbalanced voltages and set up a circulating current within the delta in both the high- and low-voltage windings. Unbalanced voltages outside the delta can, however, not produce any circulating currents within the delta, and unbalanced voltages applied to a delta-connected transformer bank cannot be equalized on the low-voltage side by the introduction of additional voltage in the delta.

As with single-phase transformers the value of the circulating current is obtained by dividing the voltage difference by the total impedance of the transformer bank. For example, if three transformers having impedances of 4 per cent are connected delta-delta, and one has a ratio 1 per cent greater than the other two, the resulting circulating current will be

$$\text{Per cent } I = \frac{1}{3 \times 4} \times 100 = 8.33 \text{ per cent.}$$

When the load is taken from such a bank, the load currents and circulating currents are superimposed, and the transformer having the highest secondary voltage will carry the greatest load, as before.

With delta-Y connected transformers a slight difference in the ratios has a very small effect compared with a delta-delta connected bank. This is due to the shifting of the neutral point, causing an equalization of the voltages.

Effect of Impedance on Parallel Operation. In addition to identical angular displacements and voltage ratios, a successful parallel operation of transformers requires that their ohmic impedances be in inverse proportion to the load which they are to carry, so that the voltage drop from no load to full load is the same in all the units, both in magnitude and phase.

The impedance of a transformer is generally expressed as the voltage drop at normal load in percentage of normal voltage. It is the resultant of two components: the resistance drop, which depends only on the ohmic resistance of the windings and is in phase with the current; and the reactance drop, which depends on the magnetic leakage between the high- and low-tension windings and is 90° out of phase with the current.

$$\text{Thus per cent } IZ = \sqrt{(\text{per cent } IR)^2 + (\text{per cent } IX)^2},$$

where IZ = total impedance drop;
IR = resistance drop of high- and low-voltage windings;
IX = reactance drop of high- and low-voltage windings.

The value of per cent IZ is easily obtained by short-circuiting one winding and measuring the E.M.F. which must be applied at the

terminals of the other winding to force full-load currents through the winding at normal frequency. The impedance may, therefore, be measured directly.

The resistance E.M.F. is equal to the high-voltage current multiplied by the equivalent resistance of the transformer, which may be obtained by measuring the resistance of both the high- and low-voltage windings, and, adding to the resistance of the high-voltage windings that of the low-voltage multiplied by the square of the ratio of transformation.

The reactance E.M.F. may be calculated from the known values for the impedance E.M.F. and resistance E.M.F. Thus

$$IX=\sqrt{(IZ)^2-(IR)^2}.$$

In the majority of power transformers, the total resistance drop is small compared to the reactance drop, in which case the per cent impedance drop (per cent IZ) can be taken as approximately equal to the per cent reactance drop (per cent IX). In many lighting transformers, however, where the reactance is made as small as possible, this cannot be done without introducing considerable error.

The following formulæ may be used for finding the division of load between any number of transformer banks operating in parallel on single-phase circuits:

$$I_1=\frac{\left(\frac{\text{kv.a.}}{\text{per cent }IZ}\right)_1}{\left(\frac{\text{kv.a.}}{\text{per cent }IZ}\right)_1+\left(\frac{\text{kv.a.}}{\text{per cent }IZ}\right)_2+;\ \dots}\times I_L,$$

$$I_2=\frac{\left(\frac{\text{kv.a.}}{\text{per cent }IZ}\right)_2}{\left(\frac{\text{kv.a.}}{\text{per cent }IZ}\right)_1+\left(\frac{\text{kv.a.}}{\text{per cent }IZ}\right)_2+;\ \dots}\times I_L,$$

where I_1 = load current in transformer bank No. 1;
I_2 = load current in transformer bank No. 2;
I_L = line current for any given load;

$\left(\frac{\text{kv.a.}}{\text{per cent }IZ}\right)_1$ = capacity rating of bank No. 1, divided by its per cent impedance;

$\left(\frac{\text{kv.a.}}{\text{per cent }IZ}\right)_2$ = capacity rating of bank No. 2, divided by its per cent impedance.

The above formulæ are, however, only correct when the relative

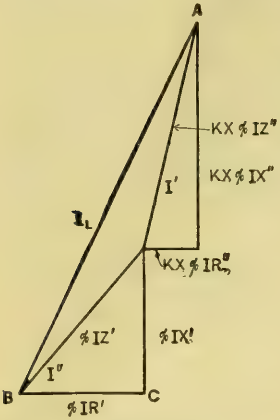


FIG. 285.

ratio between the resistance and reactance of all the transformers are equal. If not, the sum of the individual load currents will be greater than the current in the line, due to a phase difference between the currents in the different transformers. The error introduced by the inequalities in the values of this ratio is generally so small that it can be safely neglected.

When there are only two units (or banks of similar units) having impedances different in magnitude and phase angle, the division of load can be calculated very conveniently and accurately by the following graphical method (Fig. 285):

Lay out the two impedances

$$\text{per cent } IZ' = (\text{per cent } IR' + \text{per cent } IX'),$$

and

$$K_x \text{ per cent } IZ'' = (K_x \text{ per cent } IR'' + K_x \text{ per cent } IX''),$$

where

$$K = \text{kv.a.}'/\text{kv.a.}''.$$

Draw the resultant and call it I_L, the total load current in the lines. Then, per cent IZ' will represent I'', and K_x per cent IZ'' will represent I' in magnitude and phase angle, because the currents in the units are inversely proportional to their respective impedances.

Mechanical Design. For self-cooled power transformers of moderate capacity, the tanks are generally made of corrugated sheet steel, with the bottoms of the top edges permanently cast into the base and the top rim, simul-

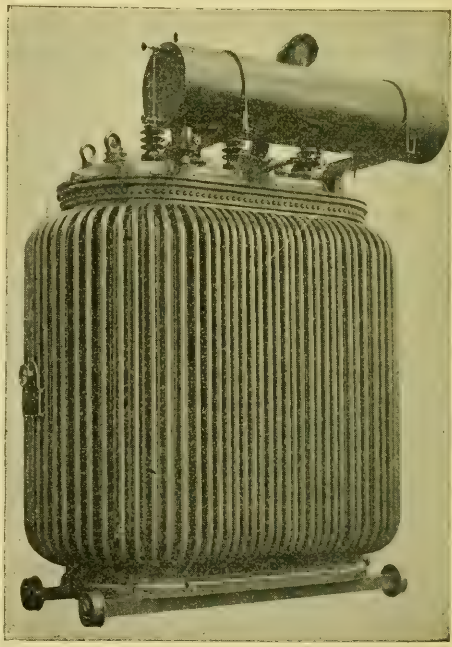


FIG. 286.—5000 kv.a., Three-phase, Self-cooled Tubular Tank Transformer.

taneously with the pouring of the castings, thus forming a perfectly cast-welded joint. For larger sizes, a tubular or radiator tank construction is usually supplied. The former are of the plain steel-plate construction with a number of wrought-iron tubes, so arranged with connections at top and bottom as to allow a natural circulation of the oil between the tank and tubes (Fig. 286). All joints are welded and are oil-tight.

The radiator tank construction (Fig. 287) has made it possible to build self-cooled transformers in any desired capacity. It consists of a main tank, either corrugated or plain, to which are attached radiators of welded, fluted steel, through which the oil circulates. If the number of radiators is not too great, they are arranged tangentially around the tank, while larger radiating surfaces are obtained by a radial arrangement. In the latter case, where the weight of the radiators acts upon a longer lever, plain steel plate tanks are generally found superior to the corrugated construction. The radiators are readily detached.

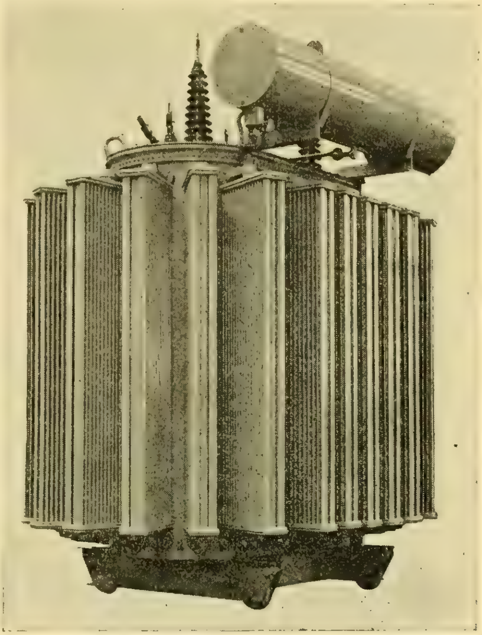


Fig. 287.—12,000 kv.a., Three-phase, Self-cooled Radiator Tank Transformer.

For water-cooled transformers, the tanks are mostly of a heavy steel-plate construction with all joints welded (Fig. 288). Sometimes a corrugated design is also used to increase the radiating surface.

It is advisable to have the transformer covers tight-fitting to prevent entrance of moisture. This is effectively accomplished by placing a gasket between the tank and the cover. Weather-proof ventilators, to prevent trapping of moisture within the tank, are essential, however, especially with large power transformers. The variation in volume of the air and oil in transformer tanks, due to the variation in the temperature of the transformer itself or that of the surrounding air, produces a constant breathing or interchange of air in the top of the tank and the

surrounding atmosphere. This breathing may result in danger to the transformer because of the lowering of the temperature of the enclosed air to the dew-point, which results in condensation of water vapor within the tank. The gradual accumulation of minute quantities of moisture will greatly decrease the dielectric strength of the oil; in the worst cases the condensation may be so rapid and so localized that large drops of water may collect, and as the specific gravity of water is greater than that of the oil, the globules of water will fall through the oil to the coils, thus resulting directly in breakdowns.

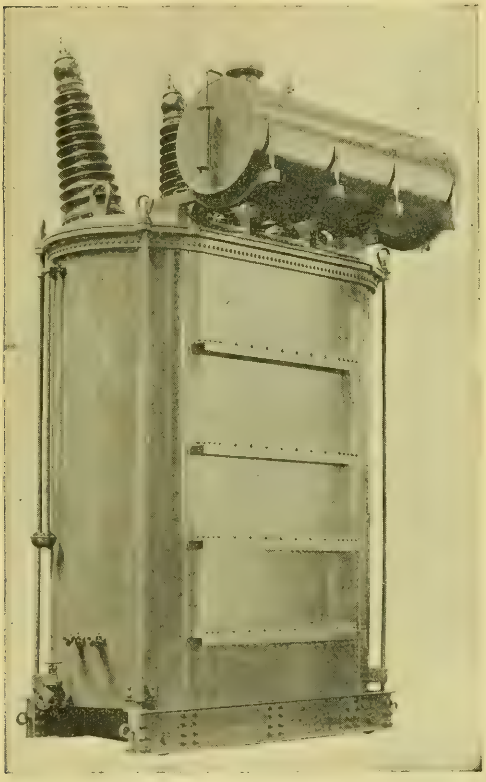


Fig. 288.—Single-phase, Water-cooled Transformer for 152,000 Volts.

In order to prevent sweating it is essential that the breathing, instead of being through crevices between the top and cover, cover and bushings, etc., should either be restricted to one opening only, in which is placed some arrangement for drying the incoming air, or else the tank should be well ventilated so that there will be a slow circulation of air within the tank, but with no possibility of rain or snow being admitted.

The former method, i.e., an air-tight tank with a chloride breather, if properly cared for, functions effectively for the conditions for which it was designed, namely, to dry the air as it is drawn into the transformer by a fall in temperature within the tank. Experience has shown that, in general, the chloride in such breathers is not properly cared for and is very often allowed to deteriorate so that the opening through the drying chamber is completely closed, and any moisture inadvertently left in the transformer which would be driven off by the heat of normal operation will condense on the cooler parts of the cover. The moisture

thus condensed may fall back on to the windings or terminal boards and cause failure of the transformer.

Experience has also shown that condensation, such as the above, will not occur in a ventilated air space such as is provided within the transformer tank by the use of two or more weatherproof ventilators. A single opening would not answer the purpose, as evaporation is effectively carried on only when currents of air automatically circulate through the air spaces above the oil in the transformer tank.

Transformers, especially those for outdoor service, should be provided with oil conservators, Figs. 288 and 289. These eliminate the air space above the oil and the isolation of the hot oil and insulation from the surrounding air. This is accomplished by completely filling the main

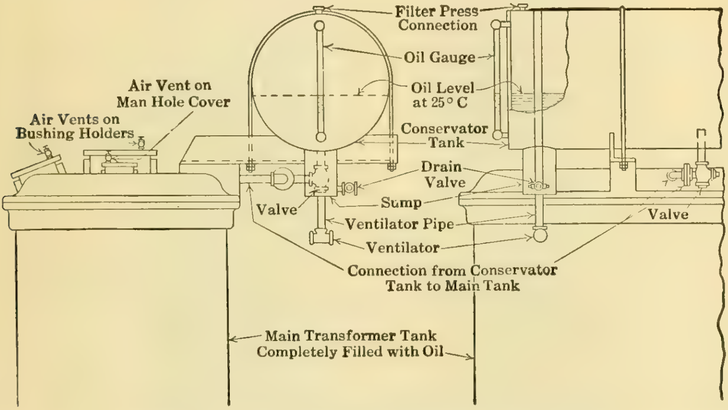


FIG. 289.—Diagram Illustrating the Main Features of the Oil Conservator.

tank with oil and providing an auxiliary tank for oil expansion, connected by suitable piping to the main tank and mounted integrally with it. The auxiliary tank is open to the surrounding air through a breathing device and is provided with a sump from which any water from condensation may be drawn off without disturbing the main tank. The connection between the two tanks is such that there can be no rapid interchange of oil; thus the oil in the auxiliary tank which is in contact with the air is kept at a relatively low temperature.

The use of oil conservators thus eliminates "breathing" and moisture condensation in the main tank, thus preserving the original insulating value of the oil. It protects the oil from "sludging," which takes place to some degree in all transformers after protracted operation, even under normal conditions, and may be accelerated to a dangerous extent during emergency overloads. Sludging is mainly due

to decomposition of the oil resulting from its exposure to the oxygen of the air while hot. The oil conservator, by preventing air from coming in contact with hot oil, greatly reduces the rate of oxidation and, thus, of sludging. Conservators also increase the life of fibrous insulation by preventing the formation of acids as well as sludge. They also prevent explosions due to ignition of a mixture of air and gas formed from hot oil above the oil level. Most tanks are suitable for indoor or outdoor service, if proper cover and bushing equipment is provided.

In order to facilitate moving, it may often be advisable to equip the transformers with wheels or trucks. If wheels alone are desired, they are usually mounted on axles attached to the base of the tank. Trucks, on the other hand, consist of a structural steel frame with wheels fitted into it. The movement is accomplished by pulling with block and tackle.

Cooling coils may be either of copper or wrought iron, the former being generally preferred. Iron coils should not be used where there are acids or alkali in the water, as these will cause a rapid corrosion. Neither should iron coils be used where the water contains a large amount of air, as in the case of water taken from shallow, rapidly moving streams, from the tailrace or penstock of a generating station, or water sprayed into an open reservoir.

Copper coils are made of seamless copper tubing with welded joints, and are subjected to a hydraulic pressure test of 500 lb. per square inch. Wrought iron coils are made of extra heavy, lap-welded wrought iron pipe with welded joints, and are subjected to a hydraulic pressure test of 1000 lb. per square inch. Brass coils are not recommended as they are subject to crystallization and galvanic action.

In large transformers, the cooling coil generally consists of two or more sections in multiple, to reduce the required water pressure. They are placed inside the upper part of the tank and securely anchored to it. They should be entirely submerged in the oil to prevent condensation of moisture. The cooling coil inlet is near the bottom of the tank, and the outlet near the top. By means of a three-way valve at the inlet, the water may be admitted to, shut off from, or drained from the coil, the draining being by gravity. A small vent at the highest point of the coil will facilitate this.

Water-flow indicators are desirable in order to enable the attendants to observe quickly that the water is flowing, inasmuch as most water-cooled transformers would overheat in a short time if the water supply were shut off. There are two kinds of flow indicators in general use, the sight-flow indicator and the check-valve indicator. The former is of the open type and consists of a funnel-shaped bowl into

which the water flows and from which it drains into the waste. The latter is constructed on the check-valve principle. It is provided with a valve rod working through a water-tight bushing and acting to close an electric circuit which, in turn, may light a lamp or operate a relay, depending on the condition of the water flow. When this is stopped or reduced below a certain point, the circuit is broken by the action of a

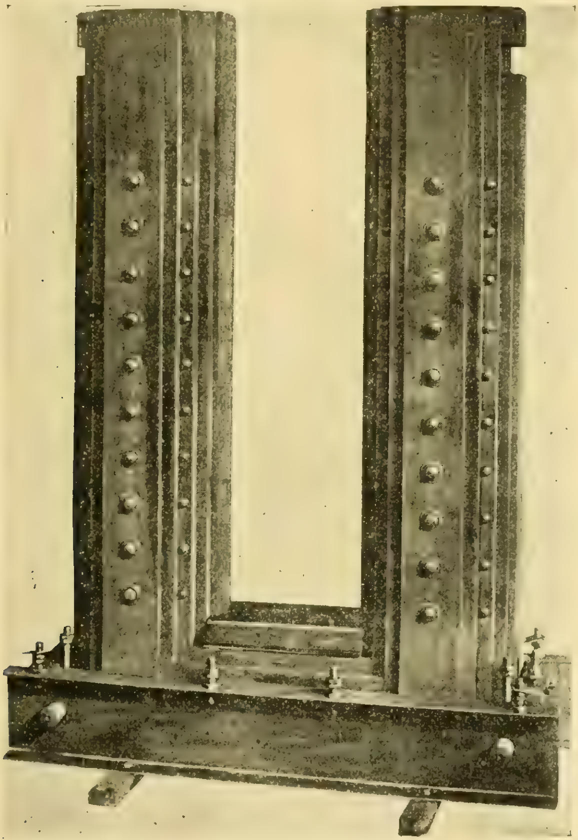


FIG. 290.—Core for 4000 kv.a. Core-type Transformer.

spring, and the lamp goes out. It may also be obtained with an indicator for use on open-circuit signal systems, in which case the signal circuit is closed when the water flow is interrupted.

As previously mentioned, most power transformers are now of the core-type design with circular coils, which makes it much easier to insulate the coils from each other, and especially the high tension from the low tension. In the shell-type design it is quite difficult to brace

the coils against mechanical forces. The forces in the individual coils tend to cause the rectangular coils to assume a circular shape, while the forces between the coils tend to cause the turns to slip by each other. If spacers are modified to prevent this, the oil circulation is impeded and the heat blanketed. In the circular-coil type, on the other hand, the forces in the individual coils, which are radial, do not tend to change the form of the coil, which already is circular. Bracing against forces between coils is done by radial spacers; and steel plates or rings braced against the core itself take the vertical thrust of the

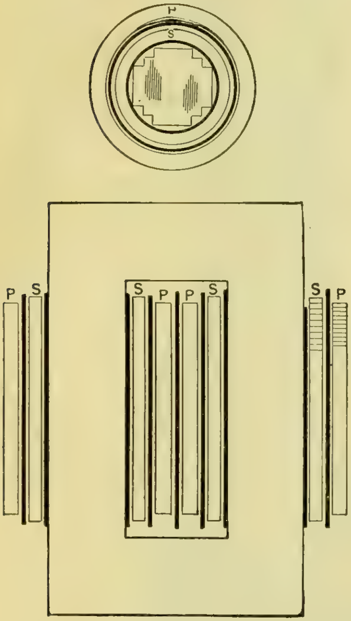


Fig. 291.—Concentric Cylinder Coil Windings for Core-type Transformers.

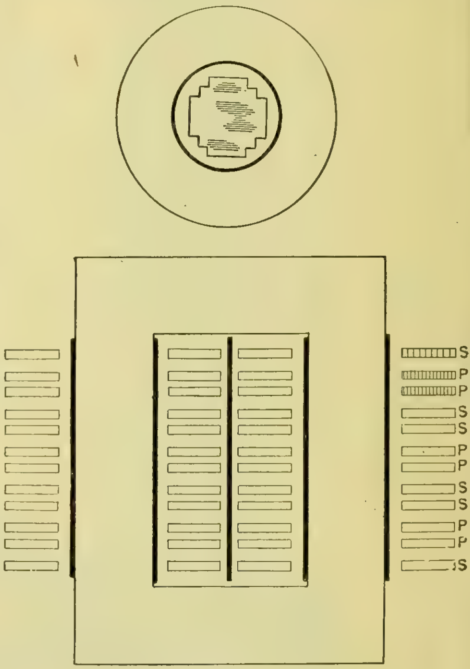


Fig. 292.—Interleaved Disc Coil Windings for Core-type Transformers.

coil stack. There is no impedance to oil circulation nor blanketing of heat.

Large, single-phase units are mostly of a two-legged construction (Fig. 290) with windings on both legs. Smaller units, however, are generally built with a three-legged, two-part distributed core, the winding being assembled on the middle section while the two other sections form the return path for the magnetic flux, their combined cross-section being approximately equal to the middle section. Three-phase units are always three-legged with windings on all legs.

The cores are built up from laminations of high-grade non-aging silicon steel of high magnetic permeability and low core loss. The laminations are insulated from one another, resulting in a low eddy-current loss. They may be assembled with alternate bolt and lap joints in a cruciform section, giving ample ventilating ducts and large core section for a given coil diameter. Riveted or bolted cores with reinforcing steel plates insure great mechanical strength and, by insulating the bolts or rivets, stray losses are avoided.

Three different winding arrangements are used with core-type transformers, the choice depending on the capacity and voltage:

1. Cylindrical, or barrel, coils assembled concentrically.
2. Disc high- and low-voltage coils assembled interleaved.
3. Barrel low-voltage with disc high-voltage assembled concentrically. With this arrangement the low-voltage coils may be either barrel, helical or even disc, depending on the voltage and capacity of the winding.

The concentric cylinder type involves a construction in which all the coils are in the form of cylinders assembled concentrically around the core legs, insulated from each other and from the core by insulating cylinders (Fig. 291). The low-voltage coils are placed nearest the core and may be wound with rectangular strip on edge or flat depending upon the number of turns and the size of conductor required. The high-voltage coils may be single- or double-cylinder edge-wound coils; or, if the size of conductor is small, the winding may be broken up into a number of small sections and wound with round wire in layers.

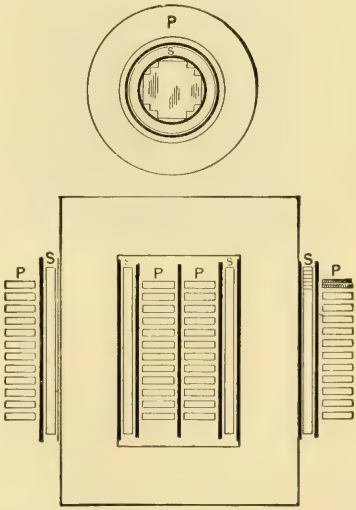


FIG. 293.—Concentric Disc-cylinder Coil Windings for Core-type Transformers.

With the interleaved construction, the coils are assembled horizontally over an insulating cylinder around the core, the primary and secondary coils being interleaved in symmetrical groups with insulating oil ducts and barriers between them (Fig. 292). They are usually wound with rectangular conductor, one turn per layer. The whole structure is securely braced at each end by plates rigidly engaging with the steel channel core clamps. There are usually four or more groups in the

windings, depending upon the capacity, voltage and the required reactance.

The concentric disc cylinder type is a combination of the above, the high-voltage coils being of the disc form and wound in the same manner as the coils for the interleaved disc type, while the low-voltage coils are cylindrical, as in the concentric cylinder type (Fig. 293). The high-voltage coil is placed outside and the low-voltage inside, next to the core, cylindrical insulations being placed between the core and the low-voltage coil, and between the high- and low-voltage coils, as in the other types.

Cylindrical coils of group 1 provide a satisfactory mechanical structure with ample radiating surface and electrical clearances for small and moderate transformers of moderate voltage. In larger sizes the greater radiating surface which is necessary is provided by breaking up the winding into disc coils separated by oil ducts. The interleaved assembly of such coils in alternate high- and low-voltage groups, group 2, gives a very sturdy design, from a mechanical point of view, which can be used up to about 60,000 volts with moderate capacities. Above this voltage, and even for lower voltages in large sizes, the concentric arrangement, group 3, is generally preferred. Figure 294 illustrates a large transformer of modern construction with this type of winding.

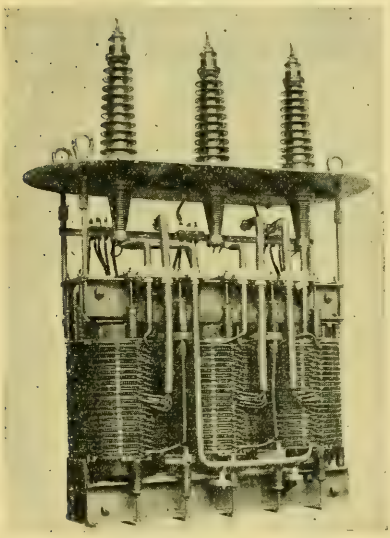


Fig. 294.—Three-phase, Disc-Cylinder Coil Transformer, Facing High-Voltage Side.

The core is insulated from the windings by one or more heavy insulating cylinders of treated fibrous material; and with concentric windings similar cylinders are used for insulation between the high- and low-voltage windings. The cylinders should be well centered with respect to the core legs, so as to provide free and reliable oil ducts. The individual coils or groups are insulated from each other by continuous disc-shaped barriers, and spacing strips provide the necessary oil ducts between the layers and coils. Certain designs employ ingenious arrangements for positively locking these spacing strips in place, thus

insuring a very rigid construction which cannot warp or shift. Increased insulation should be provided on the end turns and end coils, to protect against the high voltages which can exist on highly insulated transmission lines and which, in the form of traveling voltage waves, may strike the transformer terminals.

After the coils are wound they are clamped to dimensions and thoroughly baked and vacuum-treated to insure the complete elimination of moisture. Numerous treatments in insulating compounds are then applied, sealing up all interstices and cementing each coil into a solid structure. The coils are then subjected to further baking, after which the clamps are removed and the proper number of tapings applied, followed by the final series of treatments and bakings, after which the coils are ready for assembly. By impregnating completed stacks of coils as units, cementing all parts firmly together, a very stable and reliable construction is obtained.

After the coil stacks have been assembled on the cores, they are clamped together by heavy clamping rings, engaging the core frames at top and bottom by adjustable studs, adequate insulation being used between the coils and the rings. Such transformers are able to safely withstand the mechanical stresses incident to a complete short circuit with maintained supply voltage.

Besides affording the best mechanical support for the coil stacks, the end rings, by certain modifications, also serve a most important function as a dielectric flux distribution plate, reducing the voltage concentration on the end turns produced by line surges.

The taps are always located in the central portions of the winding where the potential strains are at a minimum. To facilitate the bringing up of several leads from the taps, a new arrangement is being used in modern transformers. It consists of multi-conductor leads, two or more insulated cables being bound together and heavily wrapped with varnished cambric, forming a stiff, solid structure that is easily supported and well insulated from ground (Fig. 294). Each element of the group terminates in a threaded stud mounted in a circular fiber disc with arrangement for interconnection by short links. To prevent the possibility of short-circuiting sections of the winding, all threaded studs, between which short circuits could be made, have the same thread and dimensions, while the studs to be connected differ in size. The connecting link is also fitted with couplings which differ in size from one another, so that unlike studs on the circular disc may be coupled. This arrangement renders harmful connections impossible.

A very convenient device for changing taps in transformers has recently been put on the market. It is known as a ratio adjuster and

is operated from the outside of the transformer tank. The tap leads are carried directly to the ratio adjuster mechanism located inside the tank, in the oil, beside the tap coils. It is operated through an insulating rod connecting the mechanism with a dial and handle, which are located outside the tank. The device is, of course, not intended for changing connections while the transformer is under load, unless special arrangements are made.

The main leads in self- and water-cooled power transformers are brought out through insulating bushings in the cover. Usually only two high-tension terminals are brought out for single-phase units, while for three-phase units three or four bushings may be provided, depending on whether the neutral is to be brought out. The same also applies to the low-tension leads.

The bushing is one of the most important parts of the transformer. According to the A.I.E.E. Rules, it must stand a dielectric test of 2.25 times the normal line voltage, plus 2000 volts, for one minute. It should have a flash-over voltage lower than its puncture voltage; that is, it should be able to withstand flash-over without puncture, so that upon application of a voltage exceeding its flash-over voltage, a flash-over of the bushing will result, and will protect it against puncture. On the other hand, it must have an instantaneous flash-over greater than the test voltage.

A good bushing must also be so designed for a considerable time lag; that is it should be slow to flash over. The protective lightning arrester spark gap, on the other hand, should be fast, that is, should have as little time lag as possible. The bushing should be entirely free from corona under normal voltage, and to accomplish this efficiently, it requires a potential distribution which is uniform along the external insulating surface of the bushing. It should of course, also be able to carry the rated current at a safe temperature.

As the altitude has an effect on the flash-over of bushings, as with other types of gaps, it should be given careful consideration in the selection of the proper size of bushing to use.

Many different types of transformer bushings are used. One manufacturer has standardized on two general classes, solid and filled bushings, both classes being suitable for both indoor and outdoor service.

Solid bushings are designed for use on voltages up to 73,000 volts. They consist of a metal tubing or rod, heavily insulated by a core made of a compound of high puncture strength and heat resistance. A grounded metal sleeve, surrounding the center portion of the core and extending from the cover of the tank to a point below the oil level,

prevents corona in the air space above the oil at all voltages. A porcelain shell, complete in one piece, protects the exposed portion of the bushing above the tank cover. With the tubular type, the conductor, consisting of a cable passing through the center metal tube, may be disconnected at the upper end of the bushing to permit the removal of the bushing without entering the tank.

The filled-type bushings are designed for operation at line voltages above 73,000. Externally, they consist of two petticoated conical porcelain shells, and an intermediate metal sleeve which extends from the cover of the tank to a point below the surface of the oil, thus preventing all corona in the air space above the oil. The joints between porcelains and metal parts are fitted with composition cork gaskets, compressed by means of metal clamping rings cemented around the ends of the porcelain shells with steam-cured Portland cement. For altitudes above 4000 feet, so-called "high altitude" bushings are usually supplied. The upper part of these bushings is lengthened, thus providing a longer striking distance to ground to compensate for the reduced dielectric strength of the air. These bushings are filled with oil and are fitted with glass gauges at the upper end to indicate the level of the oil in the bushings. For currents not over 400 amperes the conductor consists of a flexible cable passing through the central metal tube of the bushing; this conductor can readily be disconnected at the upper end of the bushing to permit its removal from the tank. Above 400 amperes, the tube itself serves as the conductor. Between the bushing and tank cover a special gasket is used, making the joint oil-tight. These filled bushings are fitted with convenient lifting lugs on the top cap to facilitate handling and installation.

Several of the transformer illustrations in this section show this type of bushing, an important feature of which is its interchangeability. With proper accessories, it may be used for transformers, oil circuit breakers, lightning arresters, current or potential transformers.

Transformers for extra high voltages, such as the 220,000-volt units recently completed for two Western power companies, embody a design somewhat different from that previously described. The advantages of the concentric winding is strikingly demonstrated with these high potentials where a very heavy insulation is required.

These transformers are of the single-phase type, with the high-voltage windings Y-connected and the neutral permanently grounded without resistance. The high-tension windings on each of the two core legs are divided into two uniform multiple circuits, the line terminal being connected to the center of the stack, and the circuit progressing either way from this point, through the windings, to the ends at top

and bottom, which therefore are substantially at ground potential. It is thus possible to omit the insulating coil supports, and the coil ends can be supported by an ordinary arrangement of oil ducts and insulating collars bearing directly against a metal support. The winding ends should be securely grounded to the core inside the tank, to make it absolutely certain that there will be no difference of potential between the neutral and the core. In addition, the tank should be grounded without resistance.

With this design it is obvious that each single-phase transformer unit only requires one high-voltage bushing. See Fig. 295.

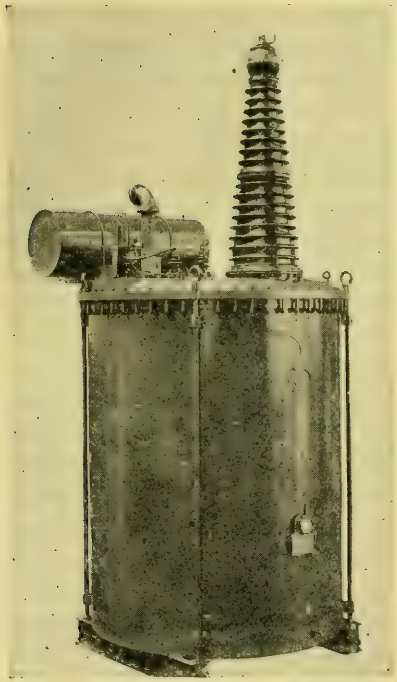


Fig. 295.—8333 kv.a., Single-phase, Water-cooled Transformer for 220,000 Volts.

Oil. Transformers should contain sufficient oil to completely immerse the core, windings and cooling coil, and a gauge should be attached to the tank in a conspicuous place to indicate the oil level, while a valve should be provided at the bottom for drawing off the oil.

Transformer oils should have good insulating properties, a high flash and low viscosity, so that the heat may be readily conducted from the coils and core to the radiating surfaces. The flash and burning points are second in importance only to viscosity, and, in fact, vary together; that is to say, an oil having a high burning-point will probably be high in viscosity, compared with another oil. It is this property of oil which makes it resist ignition until it is first heated to a certain temperature, known as its fire or burning-point, which enhances its value as an insulating and cooling medium. At a temperature somewhat below the fire or burning-point the oil gives off vapors which, as they come from the surface of the oil, may be ignited in little flashes or puffs of flame. This is known as the flash-point. The oil will not support combustion, however, until these flashes are sustained uninterruptedly, or, in other words, until the burning-point is reached. It

is, therefore, obvious that high flash and burning-points are desirable in insulating oils, in order that the fire risk attendant on their use may be reduced to a minimum.

Of extreme importance also is the percentage of deposit which may be thrown down from an oil in service. Most organic substances, when exposed to even moderate temperatures, are subject to slow changes, which, in case of oils, are probably due to chemical change, such as oxidation of some of the constituents; and when this deposit is excessive efficient cooling is very much restricted. Somewhat similar to this deposit is the jelly-like substance produced by some oils after continuous operation. In general, the higher the temperature the more rapidly these changes take place. A very slight trace of the deposit is in no degree harmful and will ordinarily only be found under the most severe conditions following a long period of service.

Transformer oils must also be watched for the presence of injurious impurities, such as acids, alkalies and free sulphur. An access of acid would result in deterioration of insulation and other materials of which the transformer is constructed. Free sulphur, even in extremely minute quantities, is seriously detrimental to the windings, the chemical action on exposed copper causing the conductors themselves to be gradually eaten through. These characteristics are, however, very carefully watched by the transformer manufacturers, so that the oils furnished are ordinarily free from such injurious impurities.

The characteristics of oils in general use vary somewhat, depending on the practice of the transformer manufacturer. One of the largest of these supplies oil of the following characteristics for its transformers:

Flash-point	140° C.
Burning-point	155° C.
Freezing-point	−5° C.
Viscosity at 40° C	52 sec.

The necessary puncture strength of oils is: 40,000 volts puncture with ½-inch discs spaced 0.2 inch apart; or, 22,000 volts puncture with 1-inch discs spaced 0.1 inch apart. The latter test is generally used.

Thermometers. In order to ascertain the temperature at which a transformer is operating, it is advisable to equip it with a thermometer, which should be so located that it can easily be read. Different thermometers are in use, those of the ordinary mercury type being generally supplied with transformers of moderate capacity. They may, if desired, be equipped with electrical contacts for connecting to an alarm circuit.

A thermometer which is very extensively used in connection with

large transformers is illustrated in Fig. 296. It depends for its operation upon the expansion of mercury in a sensitive steel tube. The bulb is connected to the indicating instrument by a small capillary steel tube, this tube being connected to a spring to which the indicating pointer is attached through a rack and pinion. The capillary tube is of such length that the bulb may be placed in the oil at the hottest part of the transformer. Variations of temperature at the bulb cause corresponding contraction or expansion of the liquid confined in this bulb,

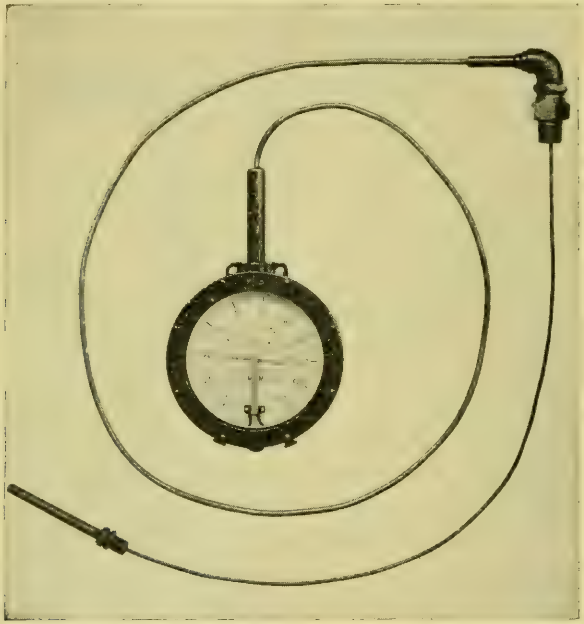


FIG. 296.—Thermometer with Electrical Conections for Use with Water-cooled Transformers.

and this is transmitted to the capillary tube connecting to the indicating mechanism. The instrument can readily be equipped with contact points for connection to an alarm circuit.

Temperature Indicators. Until it became the practice to operate transformers continuously at their maximum capacity, it was not usually important to know the internal temperature of the windings during operation. The observation of the maximum oil temperature was generally sufficient, because, while the temperature of the windings might approach the danger point, it would be only for short intervals. With the present method of rating transformers for continuous opera-

tion at 55° C. rise, it becomes important to know the actual temperature of the windings under load, because the guaranteed temperature is so much closer to the maximum safe temperature that a few degrees variation from the allowable rise may have considerable effect on the life of the transformer. It is evident that the determination of the internal temperature not only protects against over-heating but, under certain conditions, may with safety permit of greater output. This is not only true for short-time overloads but also for protracted overloads when the ambient temperature is below that specified in the A.I.E.E. Standardization Rules. It is unsafe, however, to take advantage of low ambient temperatures unless there is a dependable means for determining the maximum temperature of the windings. Again, if it is desirable to conserve cooling water, this can be accomplished with safety, provided there is an accurate indication of hot-spot temperature.

A number of schemes have been proposed for observing the hot-spot temperature of transformers. Very few, however, are suitable for practical application. This is because a thermometer, thermocouple, or resistance unit cannot be placed close enough to the winding to determine the temperature of the copper without subjecting the operator to the danger of contact with the transformer potential. When such devices are sufficiently insulated from the transformer windings to protect the operator, they are of no greater value than thermometers, as they indicate oil temperature only. If the internal temperature of the transformer windings is to be accurately and safely observed, it is necessary that the indicating unit be imbedded in the windings and, at the same time, insulated from the temperature-indicating instrument. Alternating current, must, therefore, be used to energize the temperature unit, as this allows the use of an insulating transformer in the measuring circuit.

A temperature indicator based on the above requirements has been developed by the General Electric Company, and affords a reliable and convenient means of determining, at the switchboard, the hot-spot temperature of the windings of transformers under all operating conditions. The operation of the indicating instrument depends on the variation of a non-inductive copper resistance, or so-called temperature coil, imbedded in the transformer winding. Since only a very thin insulation is required between the temperature coil and the windings, the two always have practically the same temperature. This temperature is naturally higher than the temperature of the complete winding, as indicated by resistance.

The temperature coil forms one arm of a four-armed bridge excited

from any low-voltage alternating-current circuit. (See Fig. 297.) Two arms of the bridge, *ac* and *cb*, are formed by the secondary winding of a potential transformer; the third arm consists of a constant resistance R'; while the fourth arm is the primary winding of a transformer whose secondary is connected to the temperature coil R.

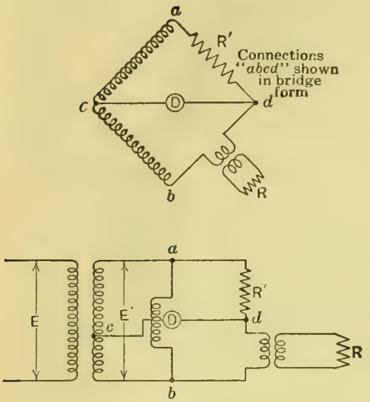


FIG. 297.—Simplified Connections of General Electric Company's Transformer Temperature Indicator.

By applying a voltage E to the primary winding of the potential transformer, a secondary voltage E' is obtained at the points a and b. It will be noted that there are three circuits between a and b, two of which, *acb* and *adb*, form the bridge, while the third, *ab*, is the fixed coil circuit of a separately excited dynamometer D. As the temperature of the observed transformer changes, the resistance of the temperature coil changes, thereby affecting the balance of the bridge and actuating the dynamometer which indicates, in degrees Centigrade, the amount of unbalancing.

While the same fundamental circuits are used as described above, the equipments contain a number of features to insure a safe and convenient operation. The panel equipment is shown in Fig. 298, the instrument having its scale graduated in 2-degree divisions from 20° to 130° C.


FIG. 298.—Temperature Indicator Panel.

Drying Transformers.—Before being shipped by the manufacturer, transformers are thoroughly dried by a vacuum process which removes all moisture from the insulation and other parts. They are, if possible, shipped filled with oil, which excludes atmospheric moisture from the windings and makes it unnecessary to dry them during installation.

If, for any reason, the windings are exposed to air, considerable moisture may be absorbed. If the atmospheric humidity is high and the transformer is idle or in storage, moisture may be absorbed directly into the oil and thence into the windings. When, for these or other reasons, drying is necessary, it can best be accom-

plished by heating the windings while submerged in oil, with the top of the tank open to the air or, at least, thoroughly ventilated. With this arrangement, the moisture will be driven off into the soil, from which it will evaporate into the air. If ventilation is not sufficient, the water vapor will condense on the cover and drip into the oil, as sometimes occurs in a transformer in service, if not dry.

When heat is generated in the windings, the oil temperature should not be allowed to exceed the specified value, since the windings are at a higher temperature and damage to insulation would result. Filtering the oil during the drying will hasten the process.

The short-circuit methods should be used whenever practicable, particularly if the transformer is new or has been out of service without oil for any length of time. The method consists in heating the windings and oil, under short circuit with a partial load on the windings, suitable oil temperature being obtained by blanketing the tank, or reducing the flow of water for water-cooled transformers. Keep the load at about 75 per cent or less of full load, so that the required oil temperature, given in the following table, will result, without endangering the windings and insulation.

The desired per cent load amperes may be obtained by short-circuiting one winding and applying to the other winding the required percentage of the impedance voltage of the energized winding. The total winding should always be loaded when this method is used, and not the tap connections. The per cent impedance voltage of the transformers involved can always be obtained from the manufacturer.

Example

Transformer rating: WC–60–3000–25,000/50,000–2300/4600/9200.
Tested full-load impedance volts = 6.5 per cent.

Connection Energized (Normal Frequency).	25,000	50,000	2,300	4,600	9,200
Imped. volts for 100 per cent amp..	1625	3250	149.5	299	598
" " " 50 " " " ..	813	1625	75	149	299
" " " 60 " " " ..	975	1950	89	179	359
" " " 70 " " " ..	1138	2276	104	209	418

The kv.a. required to dry a unit is equal to the full-load amperes of the winding to be energized, times per cent of full load amperes to be used for heat run, times normal voltage of winding to be energized, times per cent impedance.

Thus, in above case, assuming that 70 per cent of full-load amperes

is required for the heat run, and the 50,000-volt winding is to be energized, the required energy would be:

$$(60\times 0.70)\times 50{,}000\times(0.065\times 0.70)=95.5 \text{ kv.a.}$$

If the current is below 50 per cent full load, it will not be possible to heat the oil up to the desired temperature, even by completely blanketing the tank, especially if the weather is cold. Beginning at the bottom of the corrugations, wrap the tank with heavy paper, cloth, or building felt, until sufficient surface has been covered to obtain the required temperature. If the tank is equipped with radiators, or tubes, an effective means of preventing radiation from them is to lower the oil below the top inlets.

Very little heat is radiated by the tank of a water-cooled transformer; therefore, it is unnecessary to blanket the tank. The oil temperature can be held to the desired value by allowing a small flow of water to pass through the cooling coils. With water-cooled transformers, the height of the oil should be watched, as with these temperatures, sufficient expansion of oil may occur to cause leakage or overflow.

The following table gives three values of load with their corresponding maximum top oil temperatures, any one of which may be used, the choice depending upon the available power supply. It is preferable to hold the lower load current with its corresponding higher oil temperature. One hundred and twenty-five per cent load may be used at the start, if the transformer is at room temperature, until the top oil reaches 65° C.; then the load should be reduced, to obtain constant temperature in accordance with the following tabulation. The specified temperature for a given load must not be exceeded; to do so will endanger the transformer.

Short-Circuit Amperes in Per Cent of Full Load.		Maximum Top Oil Temperature in Degrees C.
Self-Cooled Trans.	Water-Cooled Trans.	
50	50	85
75	60	80
85	75	75

Transformers of the latest design are generally provided with two or more weather-proof ventilators; and additional ventilation during the drying may be obtained by slightly raising the manhole cover, protecting this opening from the weather. (This does not, of course,

apply to transformers with conservators.) If the transformer is supplied with a chloride breather, the body of this should be removed from the pipe connecting to the cover, and the end of the pipe covered with a fine-mesh screen.

The manhole cover should be watched closely during the entire process, to see that condensation does not take place. If condensation appears, either extra ventilation should be provided, or the temperature should be reduced until visible condensation stops. After the transformer has been run for eight hours, the temperature should again be raised to the limit.

The drying may be hastened by continually periodically filtering the oil, while the run progresses. In some cases, continued filtering may keep the oil temperature down to an undesirable value, and it would be better to filter only a few hours each day. It should be borne in mind that all free water must first be removed by draining, as the filter-press treatment only removes the water that is held in suspension in the oil.

During the drying run, dielectric tests of oil samples from bottom and top should be taken twice daily; these will show how the drying proceeds, by a gradual increase in the dielectric strength of the oil. The run should be continued until the oil from top and bottom tests 22 kv. or more between 1.0-inch discs spaced 0.1 inch for two consecutive tests taken twenty-four hours apart, with the oil maintained at maximum temperature and without filtering.

Another check on the effectiveness of the drying is to close the ventilating openings and operate in this manner for twenty-four hours at the maximum oil temperature. Then chill the manhole cover and examine for condensation, but do not confuse oil vapor with water condensation. Unless these tests indicate that it may be discontinued sooner, the drying should be continued at least three days after the maximum temperature has been reached.

After the short-circuit run is discontinued, the transformer should be operated at approximately two-thirds voltage, and at the same high temperature, making the same tests of oil samples, and filtering, if necessary, until the oil tests 22 kv. or above at both top and bottom of tank. After satisfactory two-third voltage test, full voltage should be applied and the same tests repeated.

Transformers that have been shipped separate from their tanks, or in tanks without oil, or have been disassembled and out of oil for three weeks or more, must be dried, preferably by the short-circuit method, before returning to service. Under favorable weather and housing conditions, transformers that have been disassembled or out

of oil less than three weeks, may be assembled, filled with good oil and returned to service with ventilation provided in the top of transformers. They should be operated in this manner for two weeks, the last week under full load, after which the manhole covers should be replaced.

It is sometimes necessary to dry out a transformer in a conservator-type tank just after it has been assembled. In such cases it has been found most satisfactory to fill the completely assembled transformer with oil having a dielectric strength of at least 22 kv., and filter the oil periodically during a short circuit run. During the run the air vents in the manhole covers, together with any in the high voltage leads or adapters, should be piped to the top of the conservator tank in such a manner that the arcing distance from any of the terminals to ground is not reduced.

The three-way valve should be turned so that oil flows between the conservator and the main tank and also out of the third outlet, to which the intake of the filter press should be connected, the filtered oil being returned to the bottom of the main tank. The transformer is brought up to temperature with loads previously mentioned and the oil filtered and the run continued until the dielectric strength of the oil becomes standard as previously outlined.

This method of filtering, which is opposite to the usual way, is preferable when drying a transformer in a conservator tank, since under drying conditions the dielectric strength of the top oil is less than that of the bottom oil.

If it becomes necessary to dry the oil during service, and a filter press is not available, it will be necessary to ventilate the transformer. Usually good ventilation must be provided, and it will be necessary to remove the pressure-relief pipe to prevent condensation in it. The transformer should be filled to about 4 inches from the top of the tank and the manhole cover slightly raised. With the oil low in this type of tank, the ground sleeve of the bushings may be out of oil, or the terminals may be too near the oil level to allow operating at normal voltage. It is recommended, therefore, that the short-circuit method be used with this type of tank, or else that the transformer be operated at half voltage, under the normal operation method of drying.

The *normal operation method* of drying may be used if the transformers are in service and show moisture condensation, but cannot be shut down to apply the short-circuit method. If the oil at the bottom and top of the transformer tests less than 16,500 volts, the filter press should first be placed in operation and the oil brought up to a dielectric strength of 22,000 volts before this method is applied.

With this method, the transformer is ventilated as before described, and to one or two of the ventilators a funnel is added, with a cheese cloth screen and a desk fan arranged so that it will blow directly into it. The manhole cover should be inspected frequently and the oil temperatures raised by blanketing the tank or by increasing the load. If condensation appears on the underside of the manhole cover, the oil temperature and the run should be reduced until the moisture disappears, after which the temperature is again raised.

The drying should be continued for three days at maximum oil temperature, in accordance with the following values.

Amperes in Per Cent of Full Load.		Maximum Top Oil Temperature in Degrees C.
Self-Cooled Trans.	Water-Cooled Trans.	
50	50	85
85	75	75
100	80	70

If no condensation is then found, the procedure described for the short-circuit run may be followed. The funnels and screens are thereafter removed and the weather-proof ventilators replaced.

Oil Drying. The necessity of occasionally drying the insulating oil in transformers, to bring it up to the required dielectric strength, has just been emphasized. Similarly oil, whether shipped in sealed barrels or in special tank cars direct from the manufacturer, may require drying at its destination before it is suitable for use in high-voltage transformers. All oil should be tested before using; but, if it is absolutely necessary to use some of the oil from the barrels before tests can be made, the barrels should be allowed to settle for several hours and then the oil pumped from the top to within 4 inches of the bottom; i.e., the oil that settles in the bottom must not be used until it can be tested and dried if necessary. Oil drums should be stored lying on their sides, with the bung down.

The method most generally used for drying and filtering oil has consisted in forcing it under pressure through several layers of blotting paper, which removes all moisture and solid matter held in suspension in the oil. A filter press, Fig. 299, has been developed for this purpose, and by this method as much as 1800 gallons of oil can be treated in an hour.

The essential portions of the filter consist of a series of alternate flat cast-iron plates and frames, the blotting paper being placed between

them, and the whole clamped tightly by means of a large screw and lever at one end. Both plates and frames have large cored holes in the lower corners, serving as inlet and outlet for the oil. The surface of the plates, except for a one-half inch rim round the edge, is grooved or corrugated both vertically and horizontally on both sides, forming the checkered, or so-called "pyramid," surface which supports the paper and forms channels communicating with the outlet at the corners. This form of surface is more efficient than a single set of corrugations or the use of perforated metal. The oil enters at the lower left-hand

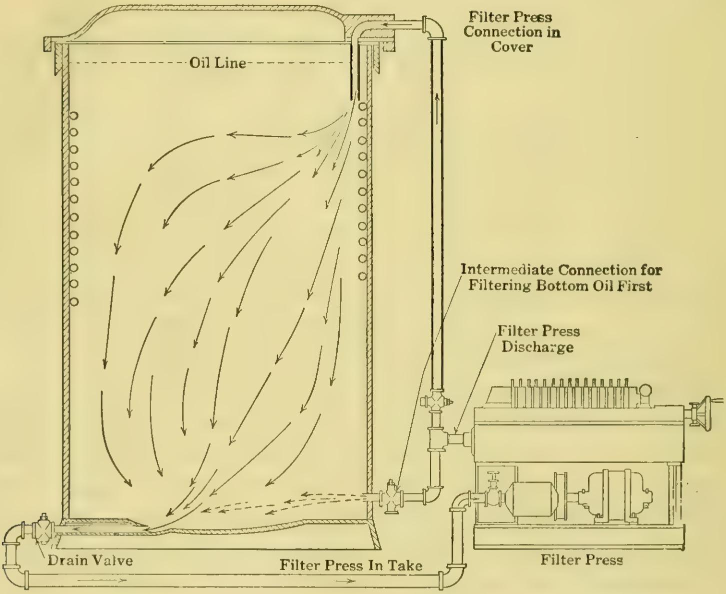


Fig. 299.—Method of Using Filter Press to Dry Oil in a Transformer under Operation.

corner of the filter passes through a series of cored holes in the plates and frames and punched holes in the blotting paper and enters and fills, in parallel, the chambers formed by the frames and plates. It then passes through the blotting paper, along the grooves of the pyramid surface, to the lower right-hand corner of the plate, and then through a series of small holes drilled from the surface of each plate to a cored passageway, similar to the inlet. A rotary plunger or multi-stage centrifugal pump is used for forcing the oil through the filters.

The filter press may be used to purify the oil without emptying the tank or interrupting the service. Transformer tanks are, for this reason,

provided with three openings for filter-press connections, Fig. 299, one at the extreme bottom (drain valve), one intermediate, about 6 inches from the base, and a third in the cover or conservator. Any dirt or free water should be drained from the bottom valve, after which the intake of the filter press is connected to the bottom opening (drain valve) and the discharge from the filter press to the top filter-press connection in the tank band or cover. The oil is then circulated through the filter press until the dielectric strength is of the required value.

If the bottom oil is very dirty and it seems desirable to filter this without disturbing the top oil, the intermediate connection for the discharge from the filter press is used while the intake remains on the drain valve. When using this connection with the transformer in service, great care is necessary to prevent pumping bubbles of air into the transformer, as these are likely to get among the coils and lead to failures. Bubbles are especially likely to get in just after the filter papers have been changed or after the oil pan has been drained, and for this reason it is recommended that the oil be filtered from these points only while the transformer is disconnected from the line. It may be necessary to renew the blotting paper quite frequently when operating in this manner. It should be noted that the intake through the filter press remains on the bottom opening (drain valve) throughout the entire filtering operation.

An electric oven for drying the blotting paper has also been developed, and forms an important part of the filtering outfit. It is divided into compartments, to permit the drying of the paper in stages, which is especially desirable during hot and humid weather. The paper should be dried for at least twenty-four hours, at or below 85° C., and then saturated with dry oil the instant it is removed from the oven, or immediately placed in the filter press before it has cooled. It should come in contact with the hands as little as possible, to prevent its absorbing perspiration.

The best oil temperature for filtering is between 25° and 75° C. Below 25° C. the viscosity increases rapidly, while at 100° C. the presses fail to remove water.

Dehydration of transformer oils has also been successfully accomplished by centrifugal action; this principle is utilized in the portable De Laval purifier shown in Fig. 300. Its construction is, in general, similar to that of the purifier used for lubricating oils, previously referred to; but when used as a dehydrator of transformer oils, its action is somewhat different. The centrifugal barrel is so constructed that it can readily be changed over for either service.

When it is used in this manner, the operator should be warned of the

possibility and danger of contaminating the transformer oil and thus predisposing it to sludge. Rigid precaution should therefore be taken to thoroughly clean all piping used in common, or else separate piping should be provided where such dual service is contemplated.

Oil-testing. The necessity of testing the dielectric strength of transformer oil has already been emphasized, and the only satisfactory method for this is the direct high-voltage test.

In taking the oil samples, great care should be exercised. None

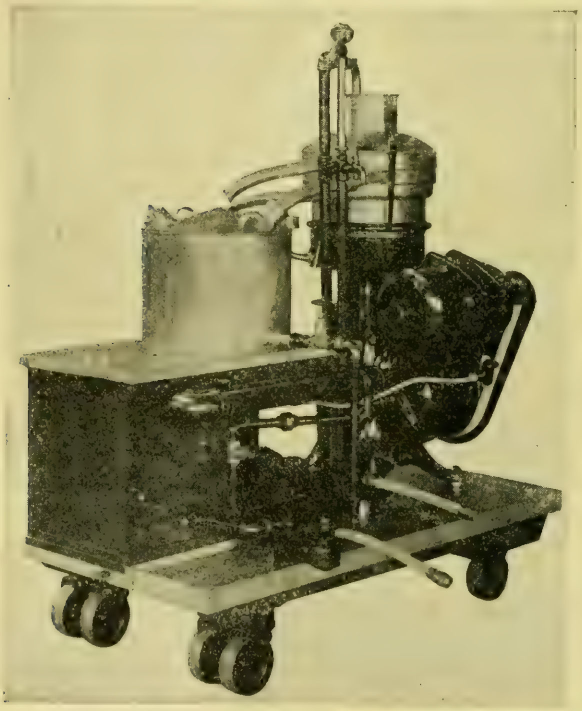


Fig. 300.—De Laval Portable Transformer Oil Purifier.

but clean receptables should be used. The first oil which is taken should be drawn into a glass receptable and examined with the eye for the presence of water. If this is present with the first sample, samples should be drawn off repeatedly until no water is visible, and, after thorough rinsing of the sample receptacle with the oil to be tested, the test sample should be obtained. It is well to test oil both from the bottom and top of transformers.

A compact oil-testing set is shown in Fig. 301. It consists of a

30,000-volt transformer, induction regulator, an oil spark gap and a suitable circuit breaker, all mounted together as a unit on a truck. The transformer is equipped with voltmeter coil to which a suitable voltmeter may be connected for reading the high-tension voltage. For routine work the regulator is equipped with calibrated dial from which a close approximation of the high-tension voltage can be read. The range of the regulator is 100 per cent, so that the voltage can be

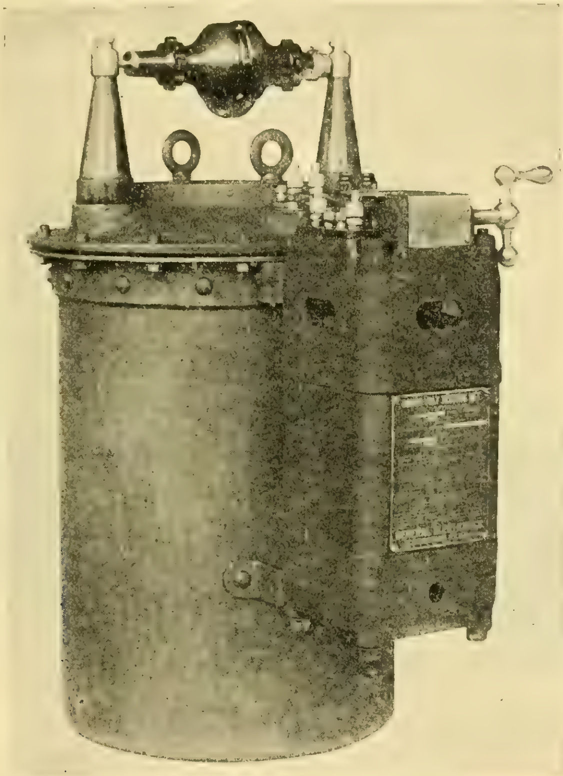


Fig. 301.—30,000-Volt Oil-testing Set.

gradually brought up from zero to maximum. The spark gap terminals have flat faces, 1 inch in diameter, and are spaced 0.1 inch apart by means of a gauge, to correspond to a test voltage of 22,000 volts. The spark receptacle should be nearly filled with the oil and allowed to stand for a moment to give bubbles time to escape, especially if the oil is cold. The rate of increase of voltage should be as fast as can be accurately read on the voltmeter, the total time of application of voltage, from zero to breakdown valve, usually being about five seconds.

The average voltage of five tests is generally taken as the dielectric strength of the oil.

Figure 302 illustrates a portable oil-testing outfit which has been developed principally for field use. It is compact and very simple in operation, and weighs only about 50 lbs., so that it may be conveniently carried in the same manner as a suit case.

The transformer has a ratio of 110 to 25,000, and the voltage applied to the testing gap is varied by means of a ratio adjuster controlling taps in an extended portion of the low-voltage winding. The dial

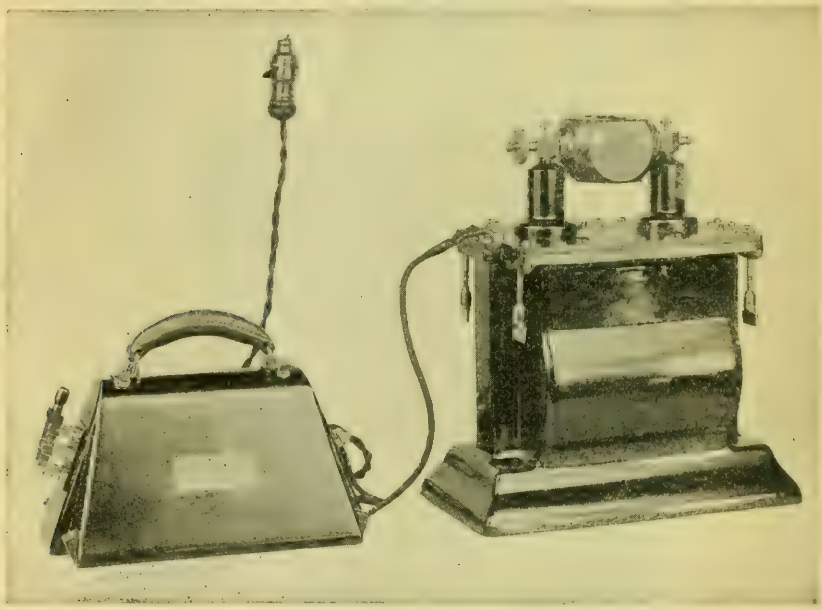


FIG. 302.—Portable Oil Testing Set.

selector switch is conveniently mounted on top of the cover. With a 110-volt supply, high-tension voltages of 15, 17.5, 20, 22.5 and 25 kv. may be impressed on the testing cup.

In case a regular oil-testing outfit is not available, a 22-kv. potential transformer may be used with an improvised water rheostat in the low-voltage side for regulating the voltage. Care should be used in interpreting the results of such tests, as distortion of wave shape may lead to incorrect conclusions.

When a testing equipment is not available and an emergency test is necessary, a small quantity of oil can be drawn off in a clean, dry

saucer, and heated very rapidly to a temperature of about 120° C., or somewhat above the boiling point of water. If a cracking noise is emitted it indicates that there is moisture in the oil. This test, however, is effective only with clean oil, and if the oil contains sediment it should first be filtered.

Operation. Artificially cooled transformers should not be run continuously, even at no load, without the cooling medium. Therefore, it is essential to maintain a proper circulation of the cooling system. If the water circulation of water-cooled transformers is, for any reason, stopped, the load should be immediately reduced as much as possible, and a close watch kept on the temperature.

The ingoing cooling water should never have a maximum temperature of over 25° C.

Nearly all cooling water will in time cause scale or sediment to form in the cooling coils. The time required to clog up a coil depends on the nature and amount of foreign matter in the water. The clogging materially decreases the efficiency of the coil and is indicated by a high oil temperature and a decreased flow of water, load conditions and water pressure remaining the same. The most frequent cause of clogging of iron cooling coils is a large quantity of air in the water, resulting in the formation of a scaly oxide. Scale and sediment can be removed from cooling coils without removing the coils from the tank. Both inlet and outlet pipes should be disconnected from the water system and temporarily piped to a point a number of feet away from the transformer, where the coil can be filled and emptied safely. Especial care must be taken to prevent any acid, dirt or water from getting into the transformer. Blow or siphon all the water from the cooling coil and then fill it with a solution of hydrochloric acid, specific gravity 1.10. (Equal parts of concentrated hydrochloric acid and commercially pure water will give this specific gravity.) After the solution has stood in the coils about an hour, flush out thoroughly with clean water. If all the scale is not removed the first time, repeat until the coil is clean, using a new solution each time. The number of times it is necessary to repeat the process will depend on the condition of the coil, though ordinarily one or two fillings will be sufficient. The chemical action which takes place is very noticeable and often forces acid, sediment, etc., from both ends of the coils; therefore, it is well to leave both ends open to prevent abnormal pressure.

When water-cooled transformers have operated for some time, especially if the operating temperatures are high, the oil may leave a deposit on the outside surface of the cooling coils. Any deposit decreases the efficiency of the coils and should be removed. This con-

dition of the coils is indicated by higher oil temperature, water flow and load conditions remaining the same. The coil should be examined whenever indications point to the formation of a deposit.

When water-cooled transformers are idle and exposed to cold, the water must be drained or blown out of the cooling coils. In addition to draining or blowing out the water, the cooling coil should be dried by forcing heated air through it. If not convenient to force heated air through the coil, enough alcohol should be poured into the coil to fill the two bottom turns of each section.

Bushings should be inspected periodically in localities where acid fumes, dust, salt, or cement deposits prevail, and the external surfaces should be wiped frequently. Lack of attention in such cases permits the formation of conducting deposits, resulting in arc-over and interruption of service.

It is recommended that oil samples be drawn and tested at least once every three months from water-cooled transformers, and once every six months from self-cooled transformers. During the first month of service of transformers having a potential of 44,000 volts or over, samples of oil should be drawn from the bottom of the tank each week, and tested. If at any time the oil should puncture below the safe voltage, the filter press may be used for treating it without taking the transformer out of service, as previously explained.

The oil level in transformers should be kept up to the mark on the oil gauge. On oil-cooled transformers with external cooling pipes or radiators, the oil must be above the top of these in the tanks, or the oil will not circulate and the transformer will overheat.

Oil-cooled transformers are occasionally operated under conditions of poor ventilation, overload, or over-voltage. Any of these conditions, or a combination of them, may raise the temperature of the oil abnormally high, causing the oil to throw down a deposit which forms on the transformer surfaces. Should the deposit on any surface, except the base, reach an average thickness of about $\frac{1}{8}$ inch, the oil should be renewed as soon as possible. Before new oil is put into the tank, the sediment should be removed from all surfaces and the windings cleaned by forcing dry, clean oil through all ducts and against all surfaces until all deposit is removed.

The compartment in which an oil-insulated self-cooled transformer is installed requires thorough ventilation. Openings for cool air must be provided at various points in or near the floor, as well as outlets in or near the roof. These openings should be 6 feet or more above the top of the transformer. The number and size of air outlets required will depend on their distance above the transformer and on the effi-

ciency and load cycle of the apparatus. In general, there should be about 20 square feet of opening for each 1000 kv.a. of transformer capacity. The total area of the air inlets should be about the same as that of the outlets. If forced ventilation is used, about 6000 cubic feet of air per minute is required for each 1000 kv.a. of transformer capacity. The temperature of the room in which the transformer is installed should not exceed the temperature of the air entering the room by more than five degrees; and presumably the entering air will come from the outside, or at least from a source not much warmer than the outside air.

The temperature should be read daily at the time of maximum load, and even more frequent readings are desirable.

The maximum oil temperature permissible under normal conditions of load and ambient is 80° C. for a self-cooled transformer and 65° C. for a water-cooled transformer. The difference between these two values is due to the difference between the temperature rises of the windings above oil in the two types, and also due to the difference in the ambient temperatures (the limiting ambient for the water-cooled being lower than that for the self-cooled). The value of 80° C. for the self-cooled type is based on an ambient temperature of from 30° to 35° C. If the ambient is from 35° to 40° C., an oil temperature of 85° C. is permissible at normal load, because the allowable " hot-spot " temperature will not be exceeded. These temperatures must not be exceeded by more than 5° C., and then only during an emergency period of short duration (less than one hour). Should the transformer remain in service any length of time under this condition it might be seriously damaged.

If a water-cooled transformer is operated at an overload, the amount of water should be increased in proportion to the load. The increased amount of water will prevent the temperature of the oil from rising as fast as the temperature of the windings, and any of the causes leading to excessive heating will have more pronounced effect under these conditions. Therefore the transformer must be watched during overload, to see that the oil temperature is kept well below the limits specified.

The oil temperature of water-cooled transformers requires watching to see that it is maintained at least 10° C. above the surrounding air. If necessary, the amount of water should be decreased.

There is practically no danger of condensation of moisture in a transformer if the oil is at all times 10° C. or more above the room temperature. The oil in an idle transformer should be kept slightly warm in order to eliminate the chances of the oil becoming moist.

This may be accomplished by applying voltage alone for a few hours each day.

The same general statements apply to combination self-cooled water-cooled transformers. When such transformers are operating self-cooled, if the load exceeds the self-cooled capacity or the indicated oil temperature is 80° C. or greater, the water should be turned on immediately and the oil temperature reduced as quickly as possible to within the water-cooled limit, that is, less than 65° C.

The effects of an increase in altitude of the location of a transformer are to increase its temperature rise (if self-cooled) and to lower the arc-over voltage of the bushings by decreasing the air density. These effects must be considered if a transformer is operated at a higher altitude than that for which it was designed. Solid bushings have a flat voltage rating and may be used at any altitude up to 10,000 feet. The voltage rating of oil and compound filled bushings varies inversely with altitude. Care must be taken when the ambient temperature is abnormally high that the transformer does not overheat; either the load must be reduced or some additional artificial cooling must be provided. If the oil temperature is abnormally high, the oil will sludge unless the transformer is supplied with a conservator. The sludge will settle on the windings and cause the temperature to increase still further; thus the effect is cumulative. If the oil in an outdoor transformer has frozen during a period of idleness, and full load is placed on the transformer, the oil will thaw and circulate before any dangerous temperatures occur. Of course, it will be impossible for any normally movable parts to operate; thus, no attempt must be made to change the position of ratio adjusters while the oil is frozen.

Oil-supply System. Many different schemes are used in laying out the oil-supply system. The piping should, however, always be arranged so that the transformers may be readily and quickly drained for inspection and in case of emergencies. This draining also refers to the piping itself. Storage tanks should be provided for both filtered and unfiltered oil, and these are generally located in the basement. Sometimes they are installed in compartments, and occasionally the tanks are further imbedded in sand, as an additional fire protection.

A flexible oil-piping system for a transformer installation is shown in the diagram (Fig. 303). This system will allow the oil to be circulated from any transformer to either tank; from one tank to the other, either directly or through the filter press; and finally, from either tank to the transformers, either directly or through the filter press. A connection to the sewer or tailrace should also be provided for draining off the oil in case of emergency. The movement of the oil

may be accomplished either by applying compressed air to the tanks or by means of the motor-driven pump of the filterpress or other separate pumps.

Occasionally an intermediate oil tank is provided and installed on the main floor or gallery, at such an elevation that the oil can be drawn into any of the transformers by gravity. The oil is then pumped from the storage tanks in the basement, after being filtered. A motor-

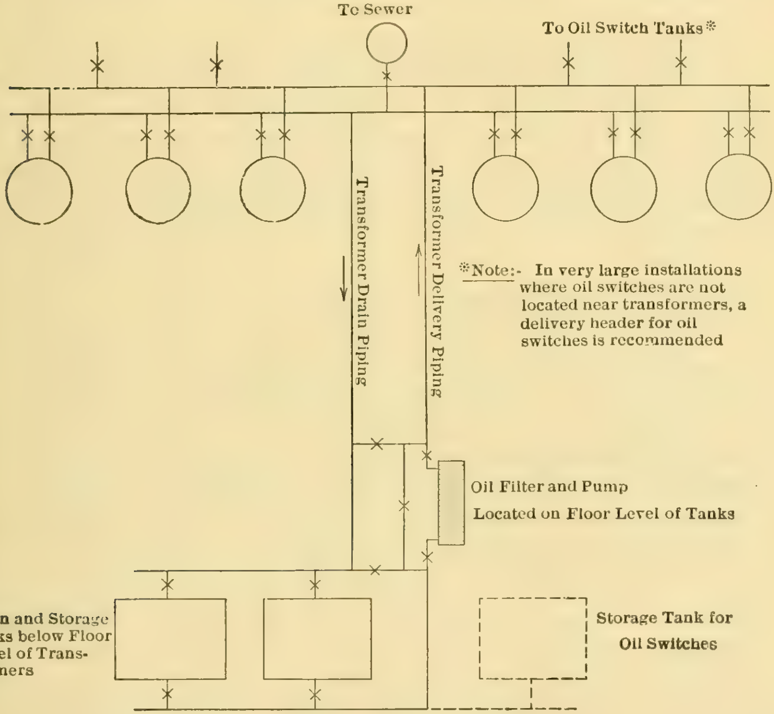


FIG. 303.—Diagram Showing Method of Arranging Transformer Oil Piping.

driven air compressor and vacuum pump may also be required, being operated as a vacuum pump for exhausting the air from the transformer cases so that the oil may be drawn into the same, or as a compressor for pumping in air in the intermediate storage tank to assist gravity in emptying the same.

Cooling-Water System. The design of the cooling-water system depends on the nature of the development, i.e., whether low-head or high-head, and also on whether a sufficient continuous water supply can be obtained. This is not the case in many substations and under

such conditions it becomes necessary to provide cooling ponds and reservoirs. The water from the pond is pumped to the transformers, and after passing through the cooling coils it is returned to the pond, where it is cooled. This may be effected either by a spray or by a basin of such dimensions that a sufficient cooling is obtained by a radiation of the heat from the water to the air. The latter method is much superior, as, when a spray is used, air is liable to be carried along with the water, causing a rapid oxidation of the iron cooling coils.

For the generating station transformers it is customary to take the cooling water from the forebay or from the penstocks. In the former case it may be necessary to provide pumps for conveying the same through the cooling coils. For high-head developments where the pressure may be too high for the cooling coils, a reducing valve must be installed, but this is, as a rule, not necessary in low-head plants or with iron cooling coils, which can withstand a much higher pressure than copper coils.

The water should be taken from at least two separate intakes, and it is needless to say that it must be free from silt and suspended particles. For this reason strainers should be provided before it enters the distributing headers, and these strainers should be so arranged that they can be readily removed and cleaned.

Auto-Transformers. A considerable saving may often be effected by using auto-transformers instead of transformers. When it is desired to effect a comparatively small change in voltage, or where both voltages are low, there is no reason why an auto-transformer cannot be used as successfully as a transformer, and the price of an auto-transformer is usually considerably less than that of a transformer for the same output.

However, auto-transformers should not, except under special conditions, be used where the difference between the high- and low-tension voltages is great, because, since the high- and low-tension windings of an auto-transformer are connected, the occurrence of grounds at certain points will subject the insulation on the low-tension circuit to the stress of the high-tension voltage.

Space will not permit an extended treatise on the many connections that may be used with auto-transformers. The reader is cautioned against using complicated arrangements without consulting an expert on the subject.

The kv.a. rating of an auto-transformer does nor refer to its output, but it gives an indication of its size, price and losses as compared with that of a transformer for the same output. In general, the rating of

a single-phase auto-transformer without taps may always be determined by multiplying the current in the high-tension line by the difference between the high- and low-tension voltages.

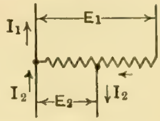


FIG. 304.—Diagrammatic Sketch of Single-phase Auto-transformer.

Figure 304 shows a diagrammatic sketch of a single-phase auto-transformer without taps, and the following general formula is given, whereby the kv.a. rating of such an auto-transformer may be determined.

$$\text{kv.a. rating of auto-transformer} = \frac{E_1 - E_2}{E_2} \times \text{kv.a. output.}$$

If, however, the auto-transformer winding is complicated by taps, it is necessary to calculate the maximum current in each section of the winding and to multiply this current by the voltage of that particular section. One-half the sum of these products will be the rating of the auto-transformer.

7. CURRENT-LIMITING REACTORS

Purpose of Reactors. Modern generating and transmission systems have reached such magnitudes as to necessitate a very careful analysis of the abnormal conditions which may take place during short circuits on the system, with a view of providing such means as may be required for protection, not only of the apparatus involved, but also of the service as a whole. This is the function of a *reactor*, by means of which the flow of current on a short circuit may be limited to a safe value. It accomplishes this purpose by reason of the voltage drop or back pressure which it exerts in the circuit.

By means of the proper installation of reactors, the whole station, or even several stations, may be operated in multiple while at the same time the several sections may be protected from each other and each section from the individual circuits which it feeds. Troubles may be localized or isolated practically where they originate, without communicating their disturbing effects.

When a short circuit occurs on a system the voltage will drop, the amount of the drop depending on the magnitude of the short circuit and the inherent characteristics of the generators, i.e., their impedance. A severe short circuit, such as may occur when there are no reactors, will cause the voltage to drop to a low value in a few cycles, whereas on a less severe short circuit, the time taken for the voltage to drop to the same low value will be longer. Synchronous apparatus will stand a complete loss of power for a few cycles only, but will stand a

reduction of voltage for a longer period. It is important then that the value of short circuit be small and that it be cleared in the shortest possible time. Introducing reactors will limit the maximum value of the current; and, with the latest type of relays, the time required for selective switch action is very short, so that a trouble can be localized and cleared before the apparatus on the rest of the system is affected.

The protective and localizing functions of a reactor are, however, quite distinct. The former, since all the evil effects of heavy current—excessive mechanical stresses, heating, etc., are proportional to the square of the current, is measured in terms involving the square of the total reactance, while the latter is measured in terms of the first power of the reactance involved.

The chief purpose of a reactor is, therefore, to limit the flow of current into a short circuit with a view to protecting the apparatus from overheating as well as failure from destructive mechanical forces; also to protecting the system as a whole against shutdown, by maintaining the voltage on part of the system while the short circuit is being cleared.

Rating. Reactors are generally spoken of as introducing a certain per cent reactance in a circuit. This is the ratio of the voltage drop across the reactor (when the rated current of the circuit at rated frequency is flowing through the reactor), to the voltage between line and neutral on three-phase circuits, or the voltage between the lines on single-phase circuits. The reactance is, therefore, expressed as being single-phase in either case.

The kilovolt-ampere (kv.a.) rating of the reactor is the product of the voltage drop across the reactor and the rated current. For generator, transformer, and feeder reactors, the rated current is usually taken as equal to the current-carrying capacity of the apparatus, while, for bus sectionalizing reactances, it is determined by the power which must be transferred over the reactor. This is very often chosen so as to correspond to the capacity of one of the generators.

Current-limiting reactors should furthermore be designed for the maximum load current they will have to carry. Being self-cooled and having neither iron nor oil to provide thermal storage, they reach their maximum temperature very quickly. Therefore, in cases where the apparatus or circuits must carry overloads for two hours or more, this overload current should be considered the rated current of the reactor, and the capacity should be selected on this basis. Under this assumption, a temperature rise of 80° C. represents common practice, the rise being based on an ambient room temperature of 40° C.

As reactors, as a rule, do not have an iron core to become magneti-

cally saturated, the reactive drop will be proportional to the current. That is, if a circuit having a 5 per cent reactor were to be short-circuited at the reactor terminal on the load side. and have full sustained voltage on the supply side, the sustained current would be limited to $100 \div 5$, or twenty times normal. It should be remembered that transformers and generators in circuit with the reactor also have definite values of reactance which, when expressed in terms of the current of the circuit (per cent reactive drop with normal current flowing) may be added directly to the reactance of the reactor to determine the total apparatus reactance of the circuit. This total reactance, plus the reactance of the line up to the point of short circuit, divided into 100, gives the approximate short-circuit current (the result being expressed in number of times normal).

Care must be exercised, in calculating the possible short-circuit current of a system, that the various per cent reactances are on the same basis, i.e., on the same current value. For example, if the reactance for a 6000 kv.a., three-phase transformer is given as 6 per cent, but a value is required which corresponds to one of the generators, having as capacity of, say, 4000 kv.a., three-phase, the corresponding value would then be $\frac{4000}{6000} \times 6 = 4$ per cent.

Similarly, it must also be remembered that reactance values given for single-phase transformers really refer to a bank of three such transformers. For example, the reactance of a 6000 kv.a., single-phase transformer is given as 3 per cent. This, then, usually refers to the full-load current from a bank of three such units, i.e., 18,000 kv.a., so that if the reactance were to be converted to the basis of a 6000 kv.a. generator, its corresponding value would be $\frac{6000}{18,000} \times 3 = 1$ per cent. A careful consideration of the above is of the greatest importance when reactance values for generators, transformers, and transmission lines of different capacities are to be combined.

For the designation of the rating of a current-limiting reactor, the following method is generally used:

"Type....... Frequency........ kv.a......... Volts Drop....... Amperes....... Reactor to give....... per cent reactive drop in....... kv.a........ volt....... phase circuit."

The type symbols generally used are CLS, CLQ and CLT.

The meaning of the symbols is as follows:

C.L.—Current-limiting reactor.

S.—Single-phase (may apply to any one reactor of a group of two or three for use in two- or three-phase circuits).

Q.—Two-phase (two single-phase reactors mounted together).

T.—Three-phase (three single-phase reactors mounted together).

For Example: A 5 per cent reactor in a 60-cycle, 6600-volt, 100-amp., single-phase circuit, means that the reactor will have a drop of 5 per cent, or 330 volts, when the rated current is flowing.

The rating of the reactor will be as follows:

C.L.S.—60 (cycles), 33 (kv.a.), 330 (volt drop), 100 (amperes) reactor—to give 5 per cent reactive drop in a 660 kv.a., 6600 volt single-phase circuit.

In the case of three-phase circuits, the percentage drop is always based on the voltage between line and neutral.

For Example: A 5 per cent reactor in a three-phase 60-cycle, 6600-volt, 100-amp. circuit means that each reactor (of the three) will have a drop of $\frac{6600}{\sqrt{3}}\times 0.05=191$ volts when normal current is flowing.

The rating will then be as follows:

C.L.S.—60 (cycles), 19.1 (kv.a.), 191 (volts drop), 100 (amperes) reactor—to give 5 per cent reactive drop in 1145 kv.a., 6600-volt three-phase circuit.

Rating as Affected by Frequency. A reactor designed for a given frequency may be used in a circuit of different frequency, in which case the per cent reactance is approximately equal to the ratio of the frequency for which it is to be used to the frequency for which it is designed times the per cent reactance for which it is designed.

For Example: A $3\frac{1}{2}$ per cent 25-cycle reactor may be used in a 40-cycle circuit, in which case the per cent reactance is approximately $\frac{40}{25}\times 3\frac{1}{2}=5.6$ per cent.

Rating as Affected by Voltage. A standard reactor can be used for lower voltage circuits than those for which it is designed, in which case the per cent reactance is *increased* in the ratio of the voltage for which it is designed to that for which it is to be used.

For Example. On an 11,000-volt three-phase circuit requiring the introduction of about $3\frac{1}{2}$ per cent reactance, it will be possible to use a 13,200 volt $3\frac{1}{2}$ per cent reactor. The reactance will be $3\frac{1}{2}\times\frac{13{,}200}{11{,}000}=4.2$ per cent.

Rating as Affected by Current. A standard reactor may be used for lower currents than that for which it is designed, in which case the per cent reactance *decreases* with the ratio of the current for which it is to be used to the current for which it is designed.

For Example. A $3\frac{1}{2}$ per cent 350-amp. reactor may be used in a 300-amp. circuit where it will insert $3\frac{1}{2}\times\frac{300}{350}=3$ per cent reactance.

From the foregoing it is seen that a $3\frac{1}{2}$ per cent, 25-cycle, 13,200-volt, 350-amp. reactor will introduce in a 40-cycle, 11,000-volt, 300-amp. circuit a reactance of approximately $3\frac{1}{2}\times\frac{40}{25}\times\frac{13{,}200}{11{,}000}\times\frac{300}{350}=5.76$ per cent.

Effect of Reactance on Power Factor. Increasing the reactance in the system results only in a slightly lower power factor, the curve in Fig. 305 showing the variation of power factor with per cent reactance. It is to be noted that if the power factor of the circuit were 90 per cent, corresponding to a reactance of 44 per cent, then the introduction of a $3\frac{1}{2}$ per cent reactor would increase the reactance to $47\frac{1}{2}$ per cent and the power factor would be lowered to 88 per cent. The introduction of a slightly larger reactor, say 4.2 per cent, would decrease the power factor to practically the same amount. On the other hand, if the power factor of the circuit were 70 per cent, the introduction of a $3\frac{1}{2}$ per cent reactor would reduce the power factor to about 66 per cent and a 4.2 per cent reactor to 65.5 per cent.

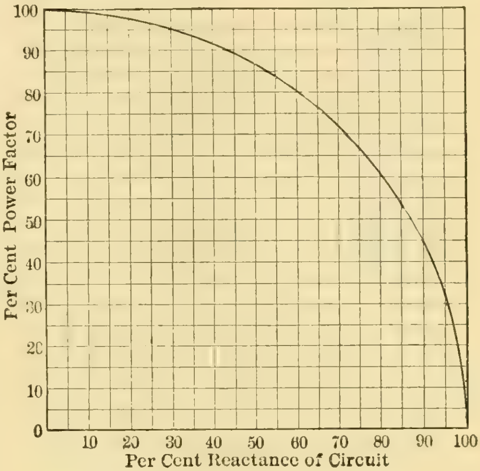


FIG. 305.

Effect of Reactance on Regulation. As in the case of the power factor, an increase in the reactance results in a slightly poorer regulation, the effect being more marked if the operating power factor is much below unity. The curves in Fig. 306 show the variation in regulation with per cent reactance, and it will be noted that, with a 90 per cent power factor, a $3\frac{1}{2}$ per cent reactor will increase the regulation 1.6 per cent, and a 4.2 per cent reactor 1.9 per cent. With a power factor of 70 per cent, the increases in the regulation would be respectively 2.5 and 3.0 per cent. However, the amount by which the voltage of the system is lowered is not seriously large and can readily be compensated for by increasing the voltage of the generators.

The above discussion shows that a reactance somewhat above that

required for current limiting protection does not materially affect the regulation or the power factor, and in many cases it may, therefore, be advantageous to use a somewhat higher reactance than that which would be required, and thereby gain the advantage of reduction in cost which can be obtained by using standard ratings.

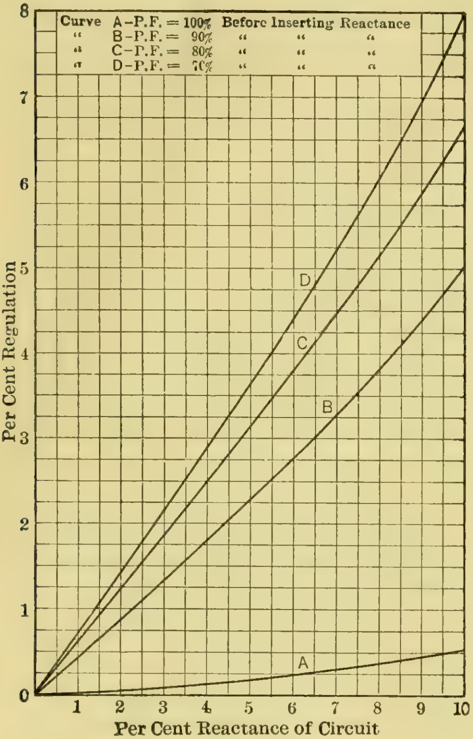


FIG. 306.

Losses. The losses in reactors are not a serious matter, but should, of course, be taken into consideration in laying out the system. They are due to the I^2R and eddy-current losses in the conductors and possibly average 5 per cent of the rating of the reactor. In some cases, however, the losses may be somewhat higher and in others considerably less.

Assume, for example, a 4 per cent feeder reactor on a 3000-kv.a. feeder; the three coils would have a combined capacity of 120 kv.a. or 40 kv.a. per coil. The losses at 5 per cent would equal about 2000 watts per coil, or 6 kilowatts on the 3000-kv.a. feeder; that is to say, one-fifth of one per cent at the maximum load of the feeder, which may last only for a comparatively short period during the day. The losses are nearly all copper losses, which go down as the square of the current; therefore, at one-half load, the losses would only be one-fourth of the above.

Bus reactors, on the other hand, carry normally very little, if any, current and the losses under normal operations are, therefore, negligible.

Inductance. The inductance of current limiting reactors may be calculated with sufficient accuracy by the following formula by Prof. Morgan Brooks:

$$L = \frac{(2\pi r N)^2}{b + 1.5t + r} \times F' \times F'' \times 10^{-9} \text{ henrys,}$$

in which (see Fig. 307),

r = mean radius of coil in centimeters;
b = axial length of coil in centimeters;
t = thickness of winding in centimeters.

Both b and t include the thickness of insulation or, if the turns are air insulated, are equal to the pitch of the winding times the number of turns. If there is only one turn, the values are equal to the diameter of the wire.

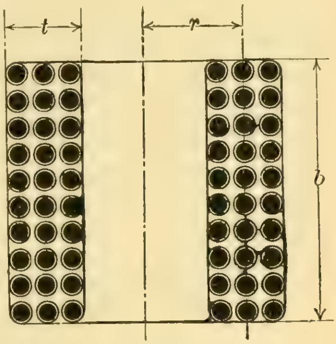


FIG. 307.—Reactance Coil.

N = total number of turns in coil;

F' and F'' are correction factors depending on the coil shape;

$$F' = \frac{10b + 13t + 2r}{10b + 10.7t + 1.4r};$$

$$F'' = 0.5 \log_{10}\left(100 + \frac{14r + 7t}{2b + 3t}\right).$$

The reactance, X, is equal to $2\pi fL$ ohms.

Location. Reactors may be located in the system in such a way that they will not only reduce the mechanical strains due to short circuit, but will also practically localize its effect to the circuit or section where it occurs. They may thus be placed in the generator leads, between the bus sections, in the low-tension transformer leads or in outgoing low-tension feeders or tie lines. Which one of the above locations or combinations thereof is preferable depends upon a number of conditions, each location having its advantages and disadvantages.

Generator Reactors. With reactors in the generator leads, the current flowing in the armature winding of the generator is limited, and this method, therefore, gives protection to the generator itself. It necessarily also limits the current that can flow into any short circuit beyond the reactors, inasmuch as the amount of current which can flow is limited to what the generators can supply. An objection to generator reactors is the fact that a short circuit on or near the busbars will cause a voltage drop on all the lines or feeders connected thereto. If the short circuit is severe, the voltage may drop to zero and this, of course, will cause all the synchronous apparatus connected to the system to drop out of step. It is, therefore, evident that reactors in the generator leads offer no protection to troubles of this nature.

The inherent reactance of slow- or medium-speed multi-polar generators in hydro-electric power systems, is, as a rule, sufficiently high,

and the construction such that the machines can safely withstand momentary short circuits, and generator reactors are very seldom used in hydro-electric plants. If such reactors are used, they should be placed in the line leads as close to the generator as possible, and not in the neutral.

Bus Reactors. These are very extensively used in hydro-electric stations and permit of an unlimited extension of the system. The busbars are divided into sections by reactors, and trouble may thereby be confined to the particular section on which the short circuit takes place, while under normal operation a free exchange of current may take place thereby retaining the advantage of parallel operation. A short circuit then can seriously involve one busbar section only, and the destructive power of a short circuit is limited to the generating capacity of that one section plus the limited power which can flow from the two adjoining sections.

The voltage of the section upon which the short circuit takes place

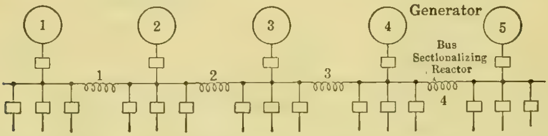


FIG. 308.—Straight Bus Arrangement Illustrating Installation of Bus Reactors.

falls to zero, and the reactors connecting the two adjacent sections each thus consume the total voltage during the transfer of the short-circuit current. The normal power transfer does not, however, take place by a drop of voltage between the sections, but by a phase displacement between the voltages of the busbar sections, as explained later.

Small and moderate capacity stations often use a *straight* bus arrangement, as illustrated in Fig. 308. For large and important installations, the arrangements of buses and reactors ordinarily used fall into two classes, which are generally known as the "star" system and the "ring" system.

The *star* system (Fig. 309) has the advantage of great flexibility and better maintenance of voltage than the ring system under short-circuit conditions. The system, arrangement and switching operations remain the same regardless of the number of bus sections in operation.

For a given value of bus reactance, the maximum variation in bus-section voltage, when power is being transferred across the bus reactors, is constant, regardless of the number of bus-sections.

The reactors, for a given limitation of short-circuit current, may be

designed to give less reactive drop than those for use in a ring system, since all of the current fed into the short-circuited section from the other sections passes through one reactor.

The current rating of the reactor, however, must in general be greater than that of a reactor for use on a ring system having a maximum equal to the current rating of one bus section, so that the kv.a. rating of the reactors is approximately the same for either system.

In order to provide complete flexibility with the star system, a transfer bus should be provided, as shown in Fig. 309, together with an additional reactor. This will enable any section of the bus to be taken out of service without changing operating conditions in any way. If it is necessary to take a generator out of service, the feeders on the affected bus section should be connected to the transfer bus, which may then be fed by any generator in the station. The two generator

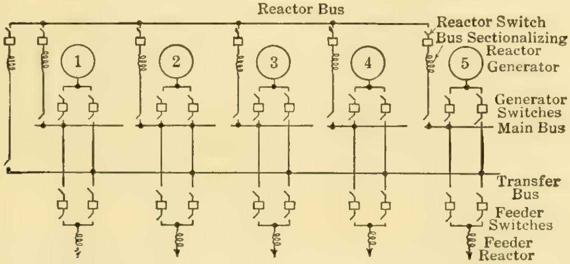


FIG. 309.—Star Bus Arrangement Including Transfer Bus, Bus Sectionalizing Reactors and Feeder Reactors.

switches then serve as a tie between the transfer bus and that bus section from which the feeders are to be energized, the transfer bus reactor switch being open. It is obvious that all the generators in the station may be called upon to furnish part of the energy required by the feeders connected to the transfer bus, in which case part of the energy will be fed direct and the remainder over the bus reactors.

The bus to which the reactors are all connected in parallel may be located conveniently to the reactors, but it must be well protected against short circuit, since it is evident that with more than two bus sections in operation, a short circuit on this bus will be more severe than at any other point on the system.

A *ring* system is shown diagrammatically in Fig. 310. With this arrangement, if one bus section is out of service the ring formation will no longer exist (unless maintained through the use of the transfer bus); in this event, it may be necessary for all the power transferred to a given bus section to pass through one set of reactors. For a given

value of bus reactance, the maximum variation in bus voltage, when transferring power across the bus reactors, increases with the number of bus sections.

The reactors, for a given current limitation, will have a greater value of reactance than those used in the star system, but the current rating may be less than for the star system, since, as long as the ring is maintained, any transfer of power between sections is through two sets of reactors in multiple. Owing to the probability, however, that the ring formation will not always be maintained, it may be desirable to design the reactors for the full current capacity of the bus section.

Transformer and Feeder Reactors. With modern high-voltage transmission systems, where the transformers are connected on the unit principle so as to form a part of the transmission line, reactors in the low-tension transformer leads may be of considerable value for protecting against short circuits in the lines, where they, of course, mostly

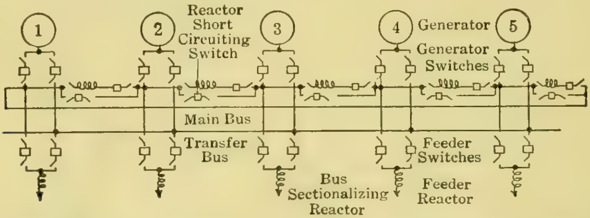


FIG. 310.—Ring Bus Arrangement Showing Transfer Bus, Bus and Feeder Reactors with Reactor Short-Circuiting Switches.

take place. Modern transformers are, however, generally built with a comparatively high inherent reactance, so that they can safely withstand short circuits, and reactors are, therefore, very seldom installed in this manner.

Reactors in low-tension feeders (Figs. 309 and 310) are very common, however, and have many advantages. The probability of a short circuit in a feeder is far greater than in any other part of the system, and the short-circuit current through a feeder switch may be considerable, since the current from all the generators will pass through the same, and possibly also the current from other synchronous machines on the system. By means of feeder reactors, however, such troubles may be still more limited than if bus reactors were provided, and it is merely a question of cost whether such reactors can be afforded.

Feeder reactors, of course, only give protection for those short circuits which occur on the feeders beyond the point where they are installed, and do not give protection to short circuits which occur on the busbars or in the generators, transformers or their connections.

Number of Reactors. The following is considered the best practice for locating reactors in various circuits:

(*a*) For *single-phase* circuits, a single reactor in one side of the line.

(*b*) For *two-phase, four-wire* circuits, two reactors, one in one side of the line of each phase.

(*c*) For *two-phase, three-wire* circuits, one reactor in each of the outside lines (as distinguished from the neutral or common wire).

(*d*) For *three-phase* circuits, one reactor in each line.

Size of Reactor. The selection of proper reactors for a system requires, first of all, a complete investigation of the possible short-circuit currents which are liable to be set up by faults in the various parts of the system. When a short circuit occurs, the maximum short-circuit current is limited by the total effective impedance at that instant in the generators, transformers, and transmission line to the fault in question. This value is, however, not constant, but decreases rapidly until a value limited by the synchronous impedance of the generators is reached (see "Synchronous Generators," page 292). A sharp distinction must, therefore, be made between an instantaneous and a sustained short circuit, the former being dependent upon the instantaneous effective impedance of the system and the latter on the sustained effective impedance. Except for long transmission and distribution lines, the resistance is, as a rule, of such small value compared to the reactance, that for all practical purposes it may be neglected, and the calculations based on reactance only instead of impedance.

As previously stated, a severe short circuit may result in a mechanical destruction of the apparatus or an overheating of the same. The former is, of course, chiefly due to the instantaneous current rush, while the sustained short-circuit current ordinarily determines the thermal effect.

The instantaneous short-circuit current is readily calculated, being equal to the normal current multiplied by 100 and divided by the total reactance to the fault, expressed in per cent. For modern water-wheel-driven generators the inherent reactance varies from 15 to 25 per cent and for transformers from 6 to 10 per cent. As expressed in per cent it may be obtained from the formula:

$$p=\frac{X\times \text{kv a.}}{10\times E^2},$$

where p = reactance in per cent;

X = single-phase reactance in ohms;

E = voltage between phases in kilovolts.

The reactance in ohms per mile of one wire of a symmetrical three-phase circuit is

$$X=2\pi fL=2\pi f\left[\left(0.74\log_{10}\frac{s}{r}+0.0805\right)10^{-3}\right],$$

in which s = spacing between centers of conductors in inches;
r = radius of conductors in inches.

In considering the amount of current that will feed into a short circuit, the synchronous apparatus connected to the system in the form of load must, of course, also be taken into account, as on a short circuit there is a tendency for such apparatus to feed back into the system, because of the inertia of the rotating elements. It is, of course, also evident that strictly " spare " equipments need not be included in the calculations.

In dealing with the effects of short circuits we must consider the damages which they may cause to generators, transformers, circuit breakers, cables or busbars, and against which protection must be provided in the form of reactors for limiting the excessive currents to values which may be safely withstood by the apparatus.

Generators and transformers are, as previously stated, now designed with such mechanical rigidity that they can safely withstand the mechanical forces arising from dead short circuits across their own terminals.

As far as oil circuit breakers are concerned, the problem is much more difficult, and their rupturing capacity is, as a rule, the limiting feature in determining the value of the permissible short-circuit current. The power that has to be broken on a short circuit naturally depends on the point of the voltage wave at which the short circuit takes place, the speed with which the circuit breaker opens, and also the rate at which the short-circuit current dies down. Owing to inertia, it is, of course, impossible for a breaker to open instantaneously, and consequently no breaker is ever called on to open the momentary short-circuit current that occurs during the first few cycles; but it has to be strong enough mechanically to resist the magnetic stresses set up during such a short circuit.

This time interval depends upon the control used to actuate the breakers, as well as upon the breaker design. Non-automatic breakers are generally selected on the assumption that they will not be operated in less than two seconds.

A breaker actuated directly by an instantaneous series A.C. trip coil (no relay) can be made to part its contacts in an extremely brief interval of time, roughly, 0.05 second; if controlled by an instantaneous

plunger-type relay actuated from the secondaries of a current transformer, the time would be about twice as much, or 0.1 second; and if induction-type relays with direct-current trip are used with the current transformers, the time will be about 0.4 second. In practice, these high speeds are not usually found necessary. Speeds ranging from 0.2 to 3 seconds will usually meet all the requirements for the selective operation of the circuits in any system. For successful selective relay operations, under practical conditions, when one is using relay-operated circuit breakers and has control over the time setting, a circuit breaker is not usually called upon to operate in less than 0.2 second. As a result, the current wave prior to the 0.2 second interval of time, in such cases, need not interest the designer in his selection of the breakers. Assuming an unsymmetrical current wave at the instant of short circuit, it will have become symmetrical for all practical purposes, at the end of 0.2 second. Therefore one need only consider a symmetrical current wave when dealing with cases of this kind.

There are many varieties of oil circuit breakers on the market, with rupturing capacities up to $1\frac{1}{2}$ million kv.a.; but the concentration of such enormous amounts of power should be avoided if possible. Some power companies thus place a limit on permissible short-circuit currents, to the equivalent of $\frac{1}{2}$ million kv.a. As a rule, switches with the higher rating will be required near the generating station; under some conditions smaller switches may be used, for instance, in substations, where the added reactance of transformers and lines serves to reduce the value of the short-circuit current.

Three-Phase Short-Circuited Calculations. Calculations for determining the current which a circuit breaker may have to interrupt on a short circuit are, as stated, generally based on the assumption that the limitation of this current is due almost entirely to the inductive reactance of the apparatus and circuits, and that the effects of resistance and capacitance are negligible. The value and persistency of this current depends also upon the characteristics of the synchronous apparatus connected to the system at the time of short circuit, and upon the point of the voltage wave at which this takes place. The current wave may thus be unsymmetrical and completely offset above or below the zero axis, thus greatly increasing the initial value of the total current wave, as explained on page 493. The current value to be ruptured is also dependent on the time that elapses between the start of the short circuit and the parting of the circuit-breaker contacts.

Messrs. Hewlett, Mahoney, and Burnham (Proceedings of the A.I.E.E., 1918), have very carefully covered this question of the influence of short-circuit currents on the selection of circuit breakers,

Table L, based on their figures, shows the rate of decay in current to be expected in the case of synchronous apparatus of modern design when subjected to short circuits through different amounts of reactance (including the reactance of the synchronous generators). The table gives the number of times normal generator current flowing during different intervals of time, for circuits of different per cent reactance (including that of the generators) expressed in per cent of total kv.a. generator capacity. They represent effective or root-mean-square values of an unsymmetrical current wave and are also based on full-load, 80 per cent power-factor excitation of the generators, thus insuring the maximum current value possible. The effect of automatic voltage regulators, in tending to increase the excitation when a short circuit occurs, has not been considered. As an appreciable time is required for the excitation to increase to its maximum value, the amount of short-circuit current is not perceptibly affected by the presence of a voltage regulator for the first half second; but from this time on the current curve is higher. (See also "Short-Circuit Current.")

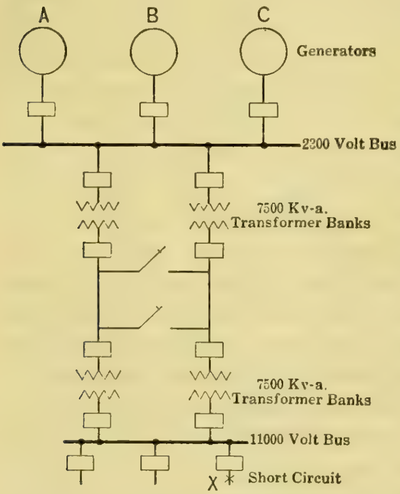


FIG. 311.—Arrangement of System of Connections, with short circuit at X.

Knowing the transient generator reactance and reactance of the circuit between the generators and the fault, one may combine these and determine the resultant per cent reactance between the generators (included) and the fault, in terms of the total generator kv.a. Then the number of times normal current flowing at any instant of time can be determined at once by simply referring to the table.

The following example will serve to illustrate the use of these curves. Assume an arrangement such as is shown in Fig. 311. With a short circuit at X, what will be the required rupturing capacity of the oil-circuit breaker in the short-circuited feeder, assuming that the breaker contacts will open in 0.1 second? The generators are all three-phase 2300 volts, the ratings and reactances being as follows:

A: 2000 kv.a., 8 per cent reactance.
B: 5000 kv.a., 12 per cent reactance.
C: 8000 kv.a., 16 per cent reactance.

TABLE L

SYSTEM SHORT-CIRCUIT CURRENT FACTORS APPLICABLE TO MACHINES WITH DEFINITE FIELD POLE STRUCTURE WITH AND WITHOUT AMORTISSEUR (SQUIRREL CAGE) WINDINGS

Time in Seconds from Instant of Short Circuit	*† R.M.S. Total Current Expressed in Number of Times Full-load Current for Various Per Cent Reactance.													
	5%	8%	10%	12%	15%	20%	30%	40%	50%	60%	75%	100%	125%	150%
Initial Rush	35.00	22.00	17.46	14.88	11.76	9.08	5.83	4.20	3.25	2.61	1.98	1.35	1.00	0.79
0.05	21.55	13.91	11.16	9.59	7.68	6.04	4.03	3.01	2.40	2.00	1.58	1.17	0.92	0.77
0.08	18.55	11.78	9.54	8.25	6.66	5.27	3.59	2.74	2.21	1.86	1.50	1.13	0.90	0.76
0.10	17.00	10.94	8.89	7.68	6.23	4.97	3.41	2.63	2.13	1.81	1.46	1.11	0.89	0.76
0.15	13.90	9.16	7.54	6.57	5.40	4.38	3.08	2.42	2.00	1.71	1.41	1.09	0.89	0.76
0.20	12.27	8.24	6.80	5.97	4.95	4.06	2.92	2.30	1.92	1.66	1.38	1.08	0.88	0.76
0.25	11.10	7.55	6.28	5.54	4.63	3.82	2.79	2.23	1.87	1.63	1.36	1.07	0.88	0.76
0.30	10.15	7.03	5.88	5.19	4.39	3.67	2.70	2.18	1.84	1.60	1.34	1.06	0.88	0.76
0.40	8.98	6.27	5.30	4.74	4.03	3.40	2.57	2.10	1.79	1.57	1.32	1.06	0.87	0.76
0.50	8.02	5.74	4.91	4.40	3.80	3.23	2.48	2.04	1.75	1.54	1.31	1.05	0.87	0.76
0.70	6.73	4.99	4.34	3.93	3.45	2.98	2.34	1.96	1.70	1.51	1.29	1.04	0.87	0.76
1.00	5.46	4.25	3.77	3.47	3.11	2.73	2.21	1.88	1.65	1.48	1.27	1.04	0.87	0.76
1.50	4.39	3.63	3.31	3.08	2.82	2.55	2.10	1.81	1.61	1.45	1.25	1.03	0.87	0.76
2.00	3.69	3.20	2.98	2.82	2.63	2.39	2.03	1.77	1.58	1.43	1.24	1.02	0.87	0.76
3.00	3.00	2.80	2.68	2.57	2.44	2.26	1.96	1.73	1.55	1.41	1.23	1.02	0.87	0.76

* Reactance expressed in per cent based on total kv.a. rating of synchronous machines. This includes both the internal reactance of the machines and the reactance of the external circuit reduced to the above basis.

† Rated full-load current based on maximum continuous kv.a. rating of synchronous machines.

NOTE.—When the equivalent reactance of line, reactor, transformer, or combination of these expressed in per cent, based on the total kv.a. rating of synchronous machines, exceeds 150 per cent, the current to be interrupted may be calculated directly from the reactance, because under those conditions the generator reactance and the time of opening of the breaker may be neglected.

The total generator kv.a. is thus 15,000. The reactances must next be converted to the same base, which is assumed to be 15,000 kv.a. This gives

$$\text{Reactance of generator } A = \frac{15{,}000}{2000} \times 8 = 60 \text{ per cent.}$$

$$\text{Reactance of generator } B = \frac{15{,}000}{5000} \times 12 = 36 \text{ per cent.}$$

$$\text{Reactance of generator } C = \frac{15{,}000}{8000} \times 16 = 30 \text{ per cent.}$$

The total combined reactance of the three generators operating in parallel on the bus will thus be

$$= \frac{1}{60} + \frac{1}{36} + \frac{1}{30} = 12.9 \text{ per cent.}$$

The transformer banks, both for stepping-up and stepping-down the voltage, are assumed to have a reactance of $6\frac{1}{4}$ per cent, based on their

normal rating of 7500 kv.a. The reactance of two banks, in parallel and based on 15,000 kv.a., will therefore be

$$\frac{6.25\times 2}{2}=6.25 \text{ per cent.}$$

The transmission lines consist of 20 miles No. 0 copper, the reactance of each line being $5\frac{1}{2}$ per cent, based on 7500 kv.a. For the two parallel lines, and based on 15,000 kv.a., the line reactance will therefore be

$$\frac{5.5\times 2}{2}=5.5 \text{ per cent.}$$

Thus, the total reactance is

$$12.9+6.25+5.5+6.25=30.9 \text{ per cent}$$

From the curves or the table, using 30 per cent reactance, we find that, for 0.1 second opening time, the current to be ruptured will be 3.41 times normal. The normal current, based on 15,000 kv.a., 11,000 volts, three-phase, is 788 amperes, and the short-circuit current therefore equals $3.41\times 788=2690$ amperes.

Where more than one source of generation, separated from the others by reactance, supplies energy to a ring network of transmission circuits, the solution becomes more involved. In such a case it is necessary to solve a series of simultaneous equations, each involving the current and potential drop in some part of the circuit. This method of solving these more complex problems is best illustrated by an example:[1]

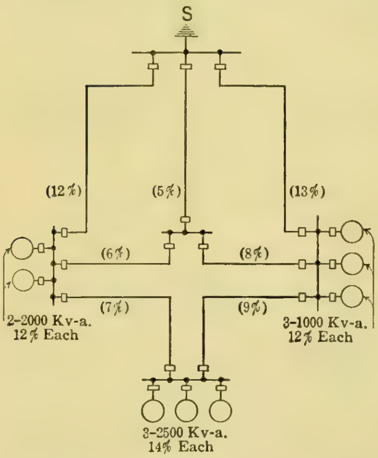


Fig. 312.—Arrangement of System Connections. (The Per Cent Reactance of Lines Given on a Base of 14,500 kv.a.)

Let Fig. 312 represent a transmission network fed by three generating stations *A*, *B*, and *C*, in which are installed two 2000 kv.a., 12 per cent reactance generators; three 2500 kv.a., 14 per cent reactance generators; and three 1000 kv.a. 12 per cent reactance generators, respectively. The per cent reactances of the different lines are as

[1] From a treatise by Ernest Pragst.

shown and are based on the total generating capacity, namely, 14,500 kv.a. Determine the current flowing at the instant of short circuit from each generating station and through each line, in the case of a fault at the point S, assuming that each generating station operates at 11,000 volts, three-phase.

This example cannot be solved in as simple a manner as the former one, for in this case several stations feed into a ring network, which greatly complicates the method of solution. In cases of this type, resort must be had to a number of simultaneous equations which represent the relation between the potential and currents flowing in the different circuits at the instant of short circuit.

Figure 312 may be simplified to appear as Fig. 313, in which the reactances of lines and generating stations are given in per cent on 14,500 kv.a. base (the total generating capacity of the system). The arrows show the assumed positive direction of flow of current in the case of a short circuit at the point S. In studying the magnitude of short-circuit currents in this assumed network, there are eleven unknown quantities with which one must deal, namely, the current flowing out of generating stations A, B, and C; that flowing through the lines D, E, F, G, H, J, and K; and that flowing into the short circuit S. The equations necessary for determining the values of current flowing through the different circuits are based on the following two principles:

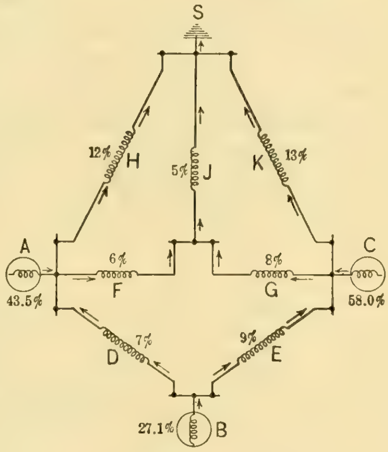


FIG. 313.—Reactance Values of Lines and Generating Stations of Arrangement Shown in Fig. 312; Given in Per Cent on 14,500 kv.a. Base.

(a) The total current flowing into any junction point of the system is equal to that flowing away from the point; and

(b) The potential drop between any generator (including drop through generator reactance) and the point of short circuit is equal to that between any other generator and point of short circuit. Or, to simplify the resultant equations, the potential drops over any number of paths between any two points of the system are equal.

[1] If the solution of the problem shows, for any circuit, a value with a negative sign, it simply means that the current flows in the opposite direction to that originally assumed.

To facilitate computations of this class, it is customary to employ relative values of current, potential and reactance; that is, to express all values of these quantities in per cent of an arbitrary base, as in the previous example; rather than in the actual terms of volts, amperes and ohms. If voltage is replaced by per cent voltage (V_p), current by times normal current of the assumed base (I_t), and ohms reactance by per cent reactance (X_p), the following relation exists between the three quantities,

$$V_p = I_t X_p,$$

which is the same relation as exists between voltage, current, and reactance.

Again referring to Fig. 313 and using values of V_p, I_t, and X_p, it is seen that the following equations express the inter-relation between the various currents, reactances, and potentials of the different circuits where A, B, and C represent the number of times normal current (normal current equals that corresponding to the assumed base, 14,500 kv.a.) flowing out of the three generating stations, A, B, and C and D, E, F, G, H, J, and K, the number of times normal current flowing through the lines D, E, F, etc.:

$$
\begin{aligned}
A &= F + H - D;\\
B &= D + E;\\
C &= G + K - E;\\
J &= F + G;\\
12H - 6F &= 13K - 8G;\\
5J &= 12H - 6F;\\
100 &= 43.5A + 12H;\\
100 &= 58.0C + 13K;\\
43.5A &= 27.1B + 7D;\\
58.0C &= 27.1B + 9E.
\end{aligned}
$$

These ten equations (value S not included) containing the ten unknown quantities, namely, the number of times normal current flowing through the various lines at the instant of short circuit, are most easily solved by first determining from one equation the value of A in terms of the other unknown quantities and substituting this value in all other equations containing A, thus eliminating A; then proceeding likewise with B, substituting its value in all remaining equations containing B, etc., until finally a value of K is found; after which all remaining unknown values can be determined by the simple substitution of known values in the previously simplified equations.

A solution of the above equations gives the following results:

$$\left.\begin{aligned} A&=1.82\\ B&=2.57\\ C&=1.38\\ D&=1.35\\ E&=1.22\\ F&=1.43\\ G&=1.03\\ H&=1.74\\ J&=2.46\\ K&=1.57 \end{aligned}\right\} = \begin{array}{l}\text{Number of times normal current of the assumed}\\ \text{base flows through each of the different lines.}\end{array}$$

As the solution of the equations, although not difficult, is rather tedious and long, and the chances of making errors are consequently great, it is always advisable to check the results. This is most easily done by remembering that the potential drop from any generator (including the drop in the generator) over any path to the point of short circuit is equal to 100 per cent. For example, take the drop from generating station B to the point of short circuit S, over the lines D, F, and J;

$$27.1B+7.0D+6.0F+5.0J=$$

$$27.1\times2.57+7.0\times1.35+6.0\times1.43+5.0\times2.46=100 \text{ per cent.}$$

The different constants and unknown quantities have been expressed in terms of the common base, 14,500 kv.a. At 11,000 volts, the current corresponding to this base is 761 amperes; hence the current flowing through each of the several circuits at the instant of short circuit is as follows:

$A_i=1386$ amperes.	$F_i=1088$ amperes.
$B_i=1957$ amperes.	$G_i=\ 784$ amperes.
$C_i=1050$ amperes.	$H_i=1325$ amperes.
$D_i=1028$ amperes.	$J_i=1873$ amperes.
$E_i=\ 928$ amperes.	$K_i=1195$ amperes.

The short-circuit current flowing into the fault S is equal to:

$$A_i+B_i+C_i=1386+1957+1050=4393 \text{ amperes,}$$

or

$$H_i+J_i+K_i=1325+1873+1195=4393 \text{ amperes.}$$

In calculating the mechanical stresses which the apparatus, such as busbars, etc., must withstand during short circuits, the instantaneous

peak value of the unsymmetrical wave must be used. This is equal to $2\sqrt{2}$ times the instantaneous effective value with a symmetrical wave. In the first example, where the total reactance was 30.9 per cent, this latter would be $\frac{100}{30.9}=3.24$ times normal current, and the instantaneous unsymmetrical peak value $2\sqrt{2}\times 3.24=9.15$ times normal current or $9.15\times 788=7200$ amperes for the 11,000 volt bus.

As far as the generators and transformers themselves are concerned, it has previously been stated that those of modern design are now being designed to safely withstand short circuits. The generator switches under the worst condition, i.e., with a short in one of the generators would be called upon to break the combined current of the other generators; as these switches, as a rule, are made non-automatic, it would only be the sustained value of the current, thus probably about two and one-half times normal value. With an automatic voltage regulator holding up the excitation, this value would, however, be greatly increased.

If the inherent reactance were very low, or the capacity of the generators very great, it might be necessary to install external reactors in the generator leads, to limit the short-circuit current which the switch would have to rupture. This is, however, never necessary in hydroelectric stations, and if such a condition should arise the bus is generally sectionalized by means of reactors as shown in Figs. 308–310.

As previously stated, the purpose of installing busbar reactors is to limit the amount of current that can flow into a fault in one section of the busbars, and so confine the disturbance to that part of the system on which the fault occurs. Bus reactors should have such a high reactance that in case of a short circuit on one bus section the voltage of the adjoining sections is not seriously disturbed by the current flowing from them over the reactors into the short circuit. On the other hand, it is highly desirable to operate all the generators of the station in parallel; and this necessitates a reactor of a low enough reactance to permit the interchange current between the bus sections to take care of the required distribution of the load along the bus.

The amount of reactance to be installed involves a careful study of the layout of the system. Probably a value allowing a transfer of power equal to the capacity of one generator (one-half from each adjacent section), may be considered sufficient. If then each generator had a short-circuit current of eight times normal full-load current, the value of the reactors would have to be 25 per cent, based on the full-load current of one generator, and the current-carrying capacity would have to correspond to one-half of the full-load current of one generator, this

being the full load on the reactor. The displacement between the sections on the above assumptions would be approximately $7\frac{1}{2}°$, a value at which the generators of the sections could safely be maintained

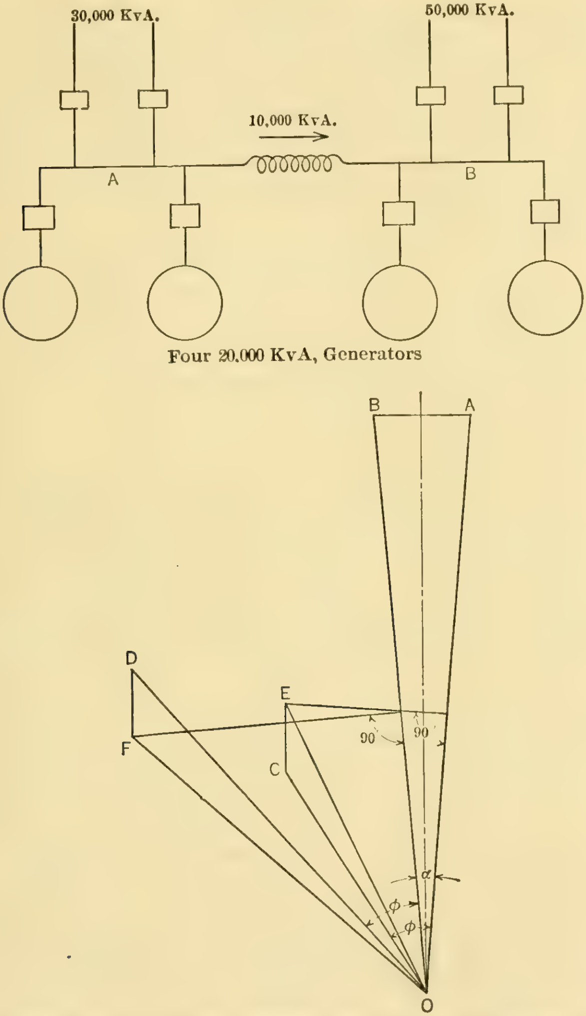


FIG. 314.—Arrangement of Bus Reactor and Diagram Showing Current and Voltage Relations.

in parallel. As a matter of fact, this could be done safely at twice this angle, and they would probably not fall out of step until the displacement was three or four times this value.

When dealing with the subject of bus reactors, it may be of interest

to consider their action a little more fully. In order to obtain some idea of the angular relations of the currents and voltages, the following case will be considered.

Assume an arrangement as illustrated in Fig. 314. The equipment consists of four 20,000 kv.a. generators, having a short-circuit ratio of eight times normal full-load current. The bus is divided in two sections by means of a reactor which will permit a power transfer equivalent to one-half the capacity of one generator, as shown. The power factor of the load is 0.8 and it is assumed that the generators are to carry equal loads and that the voltages of the two bus sections, *A* and *B*, are kept the same.

It is at once apparent that the generators on section *A* must supply 10,000 kv.a. through the reactor to section *B*; and in order to limit the amount to this value, a 25 per cent reactor is required, this figure being based on the rating of one generator. Based on the actual transfer of energy (one-half the capacity of one generator), it would be $12\frac{1}{2}$ per cent; thus, a total of 1250 kv.a., three-phase, or 416 kv.a. per single reactor.

The diagram illustrating the current and voltage relations may be constructed as follows: Draw *OA* and *OB*, representing the equal voltages of the two sections, in such a manner that *AB*, which represents the voltage across the reactor, is $12\frac{1}{2}$ per cent of *OA*. Since this voltage differs in phase from the current practically 90° (neglecting the reactor losses), it follows that the angular position of the circulating current is midway between the voltages *OA* and *OB*. *OC* represents the current on section A lagging approximately 37° ($\cos \phi = 0.8$) behind its voltage *OA*, while *OD* represents the current on section *B*, this, in turn, lagging 37° behind the voltage *OB*. *OC* and *OD* should be drawn to scale so that their lengths represent the actual proportions between the loads; i.e., *OC* should correspond to 30,000 and *OD* to 50,000 kv.a. *CE* and *DF* now represent the current flowing through the reactor, the phase position of these corresponding to the middle line between *OA* and *OB*. The current of the generators on section *A* is represented by the vector *OE*, and that of the generators on section *B* by *OF*. It will, therefore, be noted that the current through the reactor increases the load on generator *A* and decreases that on *B*. Similarly, the power factor of the load on *A* has been increased and that on *B* decreased. The projection *OF* on *OB* equals the projection *OE* on *OA*, showing that the energy delivered by the generators on each section is equal.

The size of feeder reactors depends on the size of the feeders, the relation of their capacity to that of the generators and the capacity of

the feeder circuit breakers, i.e., their safe rupturing capacity. In general, the reactor required for an overhead circuit will be less than for an underground cable, because the former usually has a higher reactance.

As an example, assume a 100,000 kv.a. station, the inherent reactance of the generators being such as to limit the short-circuit current to six times full-load current. In case of a short circuit on one of the feeders close to the busbars, not less than 600,000 kv.a. would pass into the fault, and if the capacity of the feeders were 3000 kv.a., this would be equal to two hundred times the normal capacity of the feeders, and the reactance of the generators would, therefore, only be equivalent to one-half per cent reactance in the feeders.

If now a 3 per cent reactor is placed in each feeder, the total reactance will be equal to 3.5 per cent, and the worst possible short circuit conditions would be equivalent to $\frac{3000}{3.5}\times 100=86{,}000$ kv.a., or 28.6 times the normal capacity. The voltage of the bus, instead of dropping to zero, would only be reduced to 28.6×3 or to approximately 86 per cent of its normal value.

Besides the above, the problem must also be dealt with from the point of view of economy. For example, the cost of the different types and sizes of reactors must be compared, the space occupied thereby must be considered, as well as the effect which the introduction of reactors may have in permitting less expensive switches and apparatus to be used.

In certain cases, a system may consist of such a complex network of lines as to make the calculations exceedingly difficult and the results consequently more or less uncertain. To aid in the solution of problems of this nature, an electrical device has been designed by which the results can be obtained directly and with sufficient accuracy for most practical purposes.

It consists of a table behind which are mounted a number of rheostats of the disc type, having the operating handles projecting through the vertical panel, as shown in Fig. 315. To each handle is fastened a pointer which revolves over a graduated dial on top of the table, the graduations being in per cent reactance (actually resistance). The terminals of each of the rheostats are brought out to metal blocks, fastened to the top of the table. These blocks contain holes in which may be inserted taper plugs connected together by flexible leads so that the rheostats can be interconnected in any desired manner. The resistance of the rheostats is taken as representing reactance in an actual system, and a rheostat may thus be set for any value of equivalent

reactance and plugged into the network if desired. Direct-current at 125 volts is used for operating the table, the negative side being connected to ground; and when it is desired to place a short circuit on any part of the system, that point is simply connected to the ground in such a manner as to establish a short circuit through the rheostats representing the generators and the rheostats representing the inter-connected network of lines. The current in any part of the system can be read by means of an milliammeter.

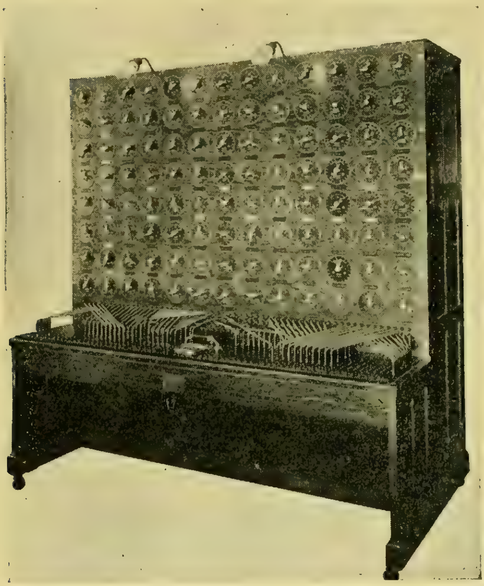


Fig. 315.—Short-circuit Current Calculating Table.

For a more complete description of this calculating table the reader is referred to the *General Electric Review*, for October, 1916, or February, 1919.

Figure 316 shows a complicated network in which a number of generators feed a common bus at points separated by busbar reactors. The percentages of reactance given are based on 45,000 kv.a. The short circuit occurs at the point *A*. The solution of this problem is rather involved, and it has been accomplished in this case by means of the calculating table described, with the results indicated on the diagram.

The values given are effective or R.M.S. values of the symmetrical wave at the beginning of the short circuit, based on instantaneous or transient reactance. They may be converted to values corresponding to Table L, as follows:

The total rated capacity of the five generators is 212,000 kv.a., and at the point of short circuit, 561,000 kv.a. The total reactance is, therefore,

$$\frac{212,000}{561,000}\times 100 = 37.8 \text{ per cent.}$$

Interpolating from the 30 and 40 per cent columns in Table L, we find

the short-circuit current in, say, 0.2 second to be 2.44 times normal, and 2.44 times 212,000 equals 518,000 kv.a. Based on no-load excitation, we therefore get the following values:

Instantaneous effective current, symmetrical wave $=$ 561,000 kv.a.

Instantaneous effective current, unsymmetrical wave $= 1.73 \times 561{,}000 = 962{,}000$ kv.a.

Peak value first half cycle, unsymmetrical wave $= 2\sqrt{2} \times 561{,}000 = 1{,}590{,}000$ kv.a.

The effective values are, as stated, used to determine the rupturing capacity of the circuit breakers with different relay settings, while the

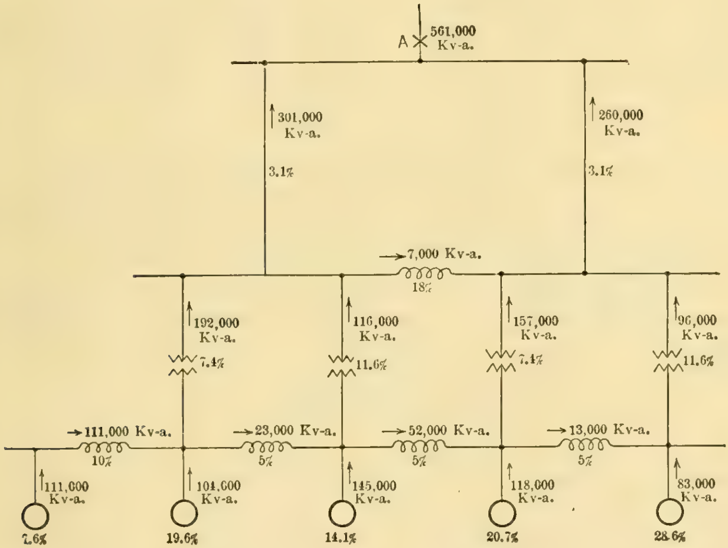


FIG. 316.—Short-circuit Current Calculations.

peak value must be considered in determining the mechanical stresses caused by the short circuits.

Single-phase Short-circuit Currents. Heretofore, we have dealt with three-phase or balanced currents. Of late years the tendency has been more and more toward the operation of systems with transformers connected in Y and neutral grounded on the high-voltage side. When a ground occurs on the line, a three-phase short circuit does not result, but rather a single-phase short circuit. A brief outline of the method used in handling such problems is given in the following, and for a more detailed study of the subject the reader is referred to an article in the *General Electric Review*, of June, 1917, by W. W. Lewis, entitled "Short-Circuit Currents on Grounded Neutral Systems."

Referring to Fig. 317: Let G represent a generator, T_1 a transformer with high-voltage winding connected in Y and neutral grounded; T_2 a transformer stepping down the voltage for the load L. The ohmic reactance of the generator is represented by x_1; of the step-down transformer by x_2; of the grounded transformer by z; of the portions of line from transformer to the point A by y_1 and y_2; and of the total length

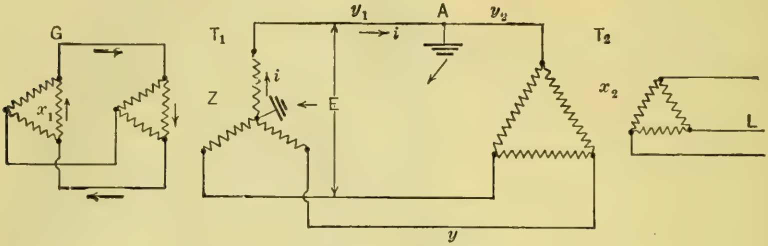


Fig. 317.—Single-phase Short Circuits.

of line by y. E is the normal high-tension voltage. All reactances, etc., are expressed in terms of their high-voltage equivalents.

Assume a ground at A. Then currents will flow as indicated by the arrows. The value of the current is expressed by the following equation:

$$i=\frac{0.577E}{x_1+z+y_1},$$

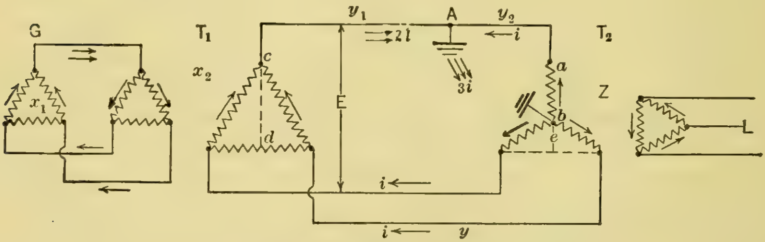


Fig. 318.—Single-phase Short-circuit Currents.

or expressed in per cent reactance on the normal three-phase line current I

$$i=\frac{100I}{\text{Per cent } Ix_1+\text{per cent } Iy_1+\text{per cent } Iz}.$$

Now consider the arrangement of Fig. 318, i.e., ungrounded transformer T_1 at the generating end and transformer T_2, with grounded neutral at the load end. The short-circuit current will flow, as indicated

by the arrows. The delta winding of transformer T_2 serves to cause equal in-phase currents to flow in each leg of the Y. The voltage drop in each part of the circuit is in phase with the voltage of the short-circuited leg $a-b$, and the total voltage drop is equal to $c-d$ or $0.866E$. The following equations may be written from the figure:

$$0.866E = i(x_1+x_2+y+2y_1)+e,$$

$$2(e-iz) = i(y_2+z);$$

from which we find

$$i = \frac{0.866E}{(x_1+x_2)+\frac{3y}{2}+\frac{3y_1}{2}+\frac{3z}{2}},$$

or expressed in per cent reactance based on normal three-phase line current I,

$$i = \frac{100I}{\frac{2}{3}(\text{per cent } Ix_1 + \text{per cent } Ix_2) + \text{per cent } Iy + \text{per cent } Iy_1 + \text{per cent } Iz}$$

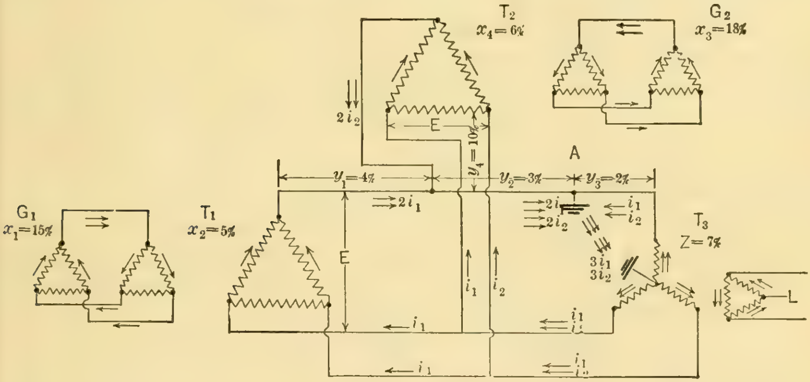


FIG. 319.—Calculation of Single-phase Short-circuit Currents.

By means of these fundamental equations, it is possible to solve problems in cases involving a number of generating stations, a network of lines, etc. As the number of generating stations increases, however, the equations increase in complexity and the solution becomes quite laborious. The labor is lessened somewhat by representing the network by an equivalent circuit with the component parts expressed in per cent reactance and solving either by the slide rule or by the calculating table.

An example will illustrate this. In Fig. 319, let G_1 and G_2 represent generators, T_1 and T_2 transformers with isolated neutrals, and T_3

a transformer with grounded neutral. The percentages of reactance based on 10,000 kv.a. 100,000 volts and three-phase are indicated.

For a ground on one line at the point A, giving a single-phase short-circuit, currents flow, as shown by the arrows. An equivalent

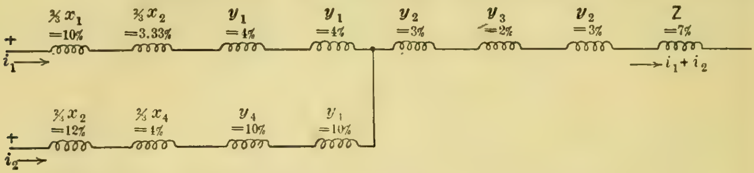


FIG. 320.—Equivalent Short-circuit Corresponding to Fig. 319.

circuit for Fig. 319 may be drawn as shown in Fig. 320. This circuit may be solved as follows:

$$10+3.33+4+4=21.33,$$

$$12+4+10+10=36.$$

$$\frac{1}{\frac{1}{21.33}+\frac{1}{36}}=\frac{1}{0.0469+0.0278}=\frac{1}{0.0747}=13.4.$$

$$3+2+3+7=15,$$

$$13.4+15=28.4.$$

$$i_1+i_2=\frac{100}{28.4}\times I=3.52\times 57.7=203;$$

$$i_1=\frac{0.0469}{0.0747}\times 203=0.628\times 203=127.5 \text{ amps.}$$

$$i_2=\frac{0.0278}{0.0747}\times 203=0.372\times 203=75.5 \text{ amps.}$$

Data Required for Short-Circuit Calculations. In order that the manufacturer may be able to make intelligent recommendations on the proper type and capacity of circuit breakers, relays, busbar supports, etc., it is essential that complete information be furnished to enable him to calculate the performance, under short circuit, of the system on which the apparatus is to be used. The following directions will serve as a guide in furnishing the desired information:

1. Supply a one-line wiring diagram showing the power line connections between generators, transformers, synchronous motors, synchronous condensers, current-limiting reactors, and principal loads, throughout the system. This diagram should also show the location of circuit breakers and dis-

connecting switches, in reference to the apparatus, buses and lines.

2. Give elevation of system above sea level.
3. Give rated kv.a. capacity, voltage, frequency and phases of principal generators, transformers, synchronous motors, synchronous converters, and synchronous condensers, also the name of manufacturer.
4. Give the per cent transient reactance [1] of synchronous apparatus, and per cent reactance of transformers and current limiting reactors. If these data are not available, give manufacturer's name, rating and serial number of apparatus.
5. Give, in the case of overhead lines, the length of lines, size, arrangement, and spacing of conductors. Where the material of conductors is other than copper, state the material.
6. State, in the case of underground cables, whether single- or three-phase cables are used, and give their length and size. Where single-phase cables are used, give spacing and arrangement of conductors. In the case of cables or buses used for the interconnection of apparatus within a station, this information is not usually necessary, as their reactances are negligible in comparison with other reactance values involved in the short-circuit calculations.
7. Give type of transformer connections employed (for example, delta, low tension; "Y" high tension). State whether the low- or high-tension neutrals are grounded. If grounded, state where and how (i.e., solid or through a resistance, or reactance). If through a resistance or reactance, give ohms resistance or reactance.
8. If recommendations are to cover the adequacy of installed circuit breakers and relays, their type and setting should be mentioned.
9. Specify method of operating the circuit breakers under consideration (whether manually or solenoid operated). If solenoid operated, state source of power and voltage.
10. If protective relay recommendations are desired, describe type and present setting of the relays and current transformer ratios used to control the principal circuits and pieces of apparatus.

[1] Transient reactance of generators, synchronous motors, or synchronous condensers is the combined reactance of both armature and field. This total reactance of the synchronous apparatus determines the initial value of short-circuit current.

11. Where power from an external source is fed into the system under consideration, it is not essential to give complete data on the system external to the one under consideration, other than the total generating capacity of the external system in kv.a., and the instantaneous symmetrical value of short-circuit current which might flow from the external system in the case of short circuit at the point of interconnection. Also give, for the external system, information asked for under item 7, relative to grounding.
12. Where plant or system extensions are contemplated, and it is desired to select the apparatus or material under consideration so that it will function successfully, not only now but also when the extensions are completed, it will be necessary to describe, in a general way, the manner in which these extensions are most likely to be made. This can be done by showing the possible future extensions in dotted lines in the diagram called for under item 1.
13. Where, (*a*) continuity of service is more essential for some circuits than others; where, (*b*) certain limitations bearing on the proposition exist; or, where, (*c*) the customer has particular ideas which he desires carried out, special reference to them should be made.

Mechanical Design. Current-limiting reactors must be designed so as not to saturate at short circuit when the full-circuit voltage comes across the reactance, and for that reason they are, as a rule, built without an iron core. There is, however, no theoretical objection to the use of iron, and if, for example, a reactor for 25 per cent were required, it would be feasible and possibly even economical to provide an iron core, which, in such a case, would have to have a normal magnetic density of one-fourth the saturation. For 3 to 10 per cent reactors, however, an excessive amount of iron would be required to prevent saturation at short circuits, thus making an iron core highly uneconomical.

The latest construction of reactors is shown in Fig. 321. It is known as the " cast-in " type because of the fact that the winding is cast and directly supported in the concrete structure, and is therefore indestructible and reliable.

The conductor, which may consist of one or several cables in multiple, is wound radially in conical layers, an ample factor of safety being preserved between each and every turn. The adjacent layers are inclined in opposite directions with ample spacings between the layers, the spacing varying with the voltage of the circuit and the num-

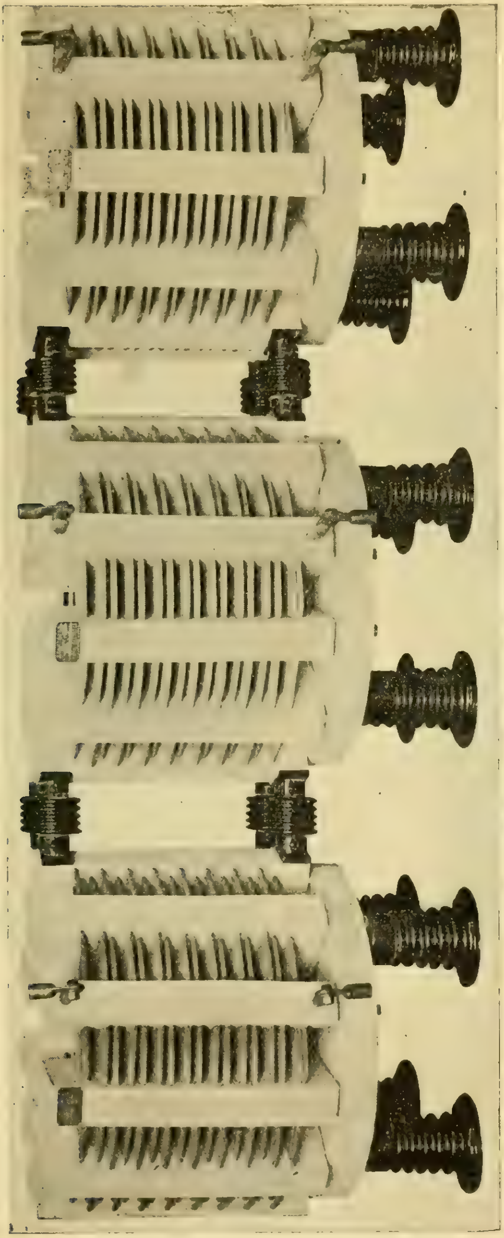


Fig. 321.—Three-phase Current Limiting Reactor of the "Cast-in" Type.

bers of layers required. Ample spacing is essential during short-circuit conditions, since there is almost always arcing at the point of short circuit, which may set up high-frequency disturbances. Any two layers thus converge toward the point where the interconnecting cross-over is made and where the maximum voltage between the layers is consequently equal to that between turns.

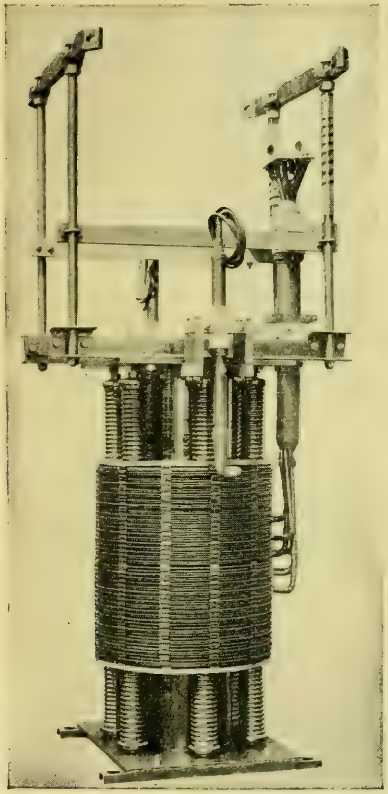


Fig. 322.—Internal View of an Oil-insulated Reactor for a High-voltage Circuit.

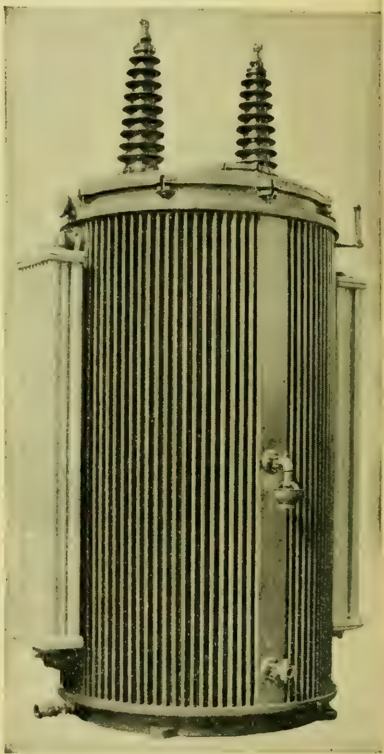


Fig. 323.—External View of an Oil-insulated Reactor for a High-voltage Circuit.

The windings are held rigidly in their position by the vertical coil supports, which are cast around the turns after these have been wound in a form. The concrete is thereafter cured under high steam pressure, which gives it a mechanical strength obtained in no other way. The coil is mounted upon a concrete base in the form of a ring with rectangular section, and the base is supported from the ground by means of

porcelain post insulators. Reactors of a three-phase group should be securely braced from each other by porcelain braces, to withstand mutual forces of attraction between the three reactors. Such braces are essential unless the reactors are placed far enough apart to reduce the stresses to safe values, the minimum distance generally being specified by the manufacturer.

High-voltage Reactors. With the ever-increasing size of electric power plants, and the inter-connection of systems through their high voltage networks, accidental short circuits on these high-voltage lines have become a matter of very serious concern. The energy available to pour forth into short circuits has increased from the period when a short circuit simply meant a discontinuance of a line until the trouble could be cleared up, to the present time when such short circuits are fraught with great danger of destruction to life and property. For this reason there has come a demand for high-voltage current-limiting reactors.

Figures 322 and 323 show such a reactor, in which the windings are constructed and insulated in the same manner as in a transformer. Because of the high voltages for which these reactors are designed, they are immersed in oil and contained in steel tanks.

These reactors do not have iron cores, for the reason that they are used for current-limiting purposes and therefore necessarily must have straight-line volt-ampere characteristics. They have consequently a very large stray magnetic field which, if not confined, would pass into the containing tank and cause excessive losses. This stray field is confined by placing a short-circuited winding adjacent to the walls of the tank, which prevents the flux from flowing into the tank. In water-cooled reactors the copper cooling coil is short-circuited and utilized for the flux-shielding winding.

Voltage Stresses in Reactors. Reactors, in service, may be subjected to very high-voltage stresses. These stresses may be caused by high-voltage impulses due to lightning discharges near the overhead lines; or, if the reactors are placed in systems of high power and large capacitance, there may be high voltages due to resonance. To guard against these dangers, a non-inductive of special characteristics has been developed; when it is installed in shunt with the reactor, the resistance will by-pass and consume the energy of the voltage disturbances. One make of such resistors consists of carborundum rods cast in concrete and installed in the central space of the reactor coil.

For a further study of this subject of voltage stresses in reactors in service, the reader should consult the paper presented before the A.I.E.E., July 1, 1920, by Messrs. Kierstad and Meeker.

8. SWITCHING EQUIPMENT

The engineering problems in connection with the operation of high-voltage hydro-electric transmission systems are very largely those which have to do with preventing interruptions to the service and with isolating and localizing electrical disturbances before they can become general. These problems resolve themselves into a careful study of the general design of the apparatus and of the best possible arrangement of the different circuits and the method of switching. Reliability and continuity of service are the main considerations, but besides this the protection of the apparatus from injury should not be lost sight of.

The switching equipment is the key to the entire system, and the first requisite to decide on is the system of connections, the diagram of which should be worked out with the greatest care, taking into consideration the various equipments and the normal, as well as possible abnormal, operating conditions of the entire system. The design of the control boards and the selection and arrangement of the oil circuit breakers, busbars, etc., depends greatly on the system of connections; so, in fact, does the design of the entire power station.

In taking up the various problems dealing with the design of a switching equipment, space will only permit the fundamental principles to be dealt with, and only some of the more important apparatus can be briefly described. It would be of little value to go into the minute details of the engineering features connected with a switching equipment, because the art changes so rapidly, and new and improved lines of apparatus are brought on the market so rapidly, that they change for almost every new important installation.

System of Connections. In laying out the system of connections and switching equipment for a high-tension transmission system, there are a number of general principles which must be kept clearly in mind. Chief among these is continuity of service, which is now of prime importance, having been made so by the steadily increasing demand for a much higher standard of service than formerly. This, in turn, involves a flexibility in the arrangement of the connections, so as to reduce to the absolute minimum the amount of apparatus which will be automatically disconnected in case of trouble, and also to provide for sectionalizing any apparatus for inspection and repairs. Besides this, the protection of the apparatus from injury should be given careful study. These considerations are, however, very closely connected and must naturally be treated together. In this connection it should be noted that the function of an automatic selective switching is no

longer correlated with the idea of protecting the apparatus against ordinary overloads, but that the relays are intended to operate only on breakdowns, although their setting is usually given in per cent overload of the rated capacity of the circuit.

The particular system of connections to be used depends obviously on the conditions to be met, and each system must be studied and an individual solution applied. There are, however, many points of similarity, and the solution in one case will serve as a partial guide, at least, in others. In any event, the system as a whole should be carefully considered in deciding on the connections, and the conclusions should not be based on the condition in a generating station or a substation alone. The characteristics of the customer's load conditions must be carefully investigated, and future probable loads and additions predetermined as far as possible.

It is especially essential to provide an uninterrupted service for large and important customers, as the success of the project depends in most cases entirely on the ability to maintain a satisfactory service for these. The smaller customers must also, of course, be considered and given the best service possible. For this reason, the power to important customers is often supplied from two sources, that is, from two sub-stations or by means of double-line circuits, etc. Two such sources of supply are, of course, the ideal arrangement, in which case one of them would be automatically cut out in case of trouble while the other would be kept in operation and continue to carry the load. This, however, is not always possible for every customer.

In a general way, the service of a large power system, with its transmission and distributing lines, can be likened to a combined express and local train service of a transportation company. The transmission lines feeding the different sub-stations on the system correspond to the express trains, and must be absolutely free from interruption, for which reason such lines should be so arranged that any sub-station is fed by two independent circuits. The local train service would, on the other hand, correspond to the distributing lines, and any interruptions which might be permitted to occur, should be confined to these local circuits. Of course, if the service demands, even these circuits can be installed in duplicate.

In a power transmission system the chief source of trouble is always the transmission line, and the trouble can usually be traced back to the insulators. This subject of the design of insulators has been studied very carefully during the past few years, and great improvements have been made in their reliability. Together with atmospheric disturbances in districts frequented by lightning storms, the deterioration of insu-

lators makes the transmission line a vulnerable part of the system, and the largest percentage of troubles is caused thereby. Apparatus troubles are, furthermore, often traced directly to line troubles as a secondary cause, through arcing grounds, surges, etc.

It is evident from the above that the system of connections depends entirely on the conditions to be met. Almost every installation has certain features which require that the switching arrangements be

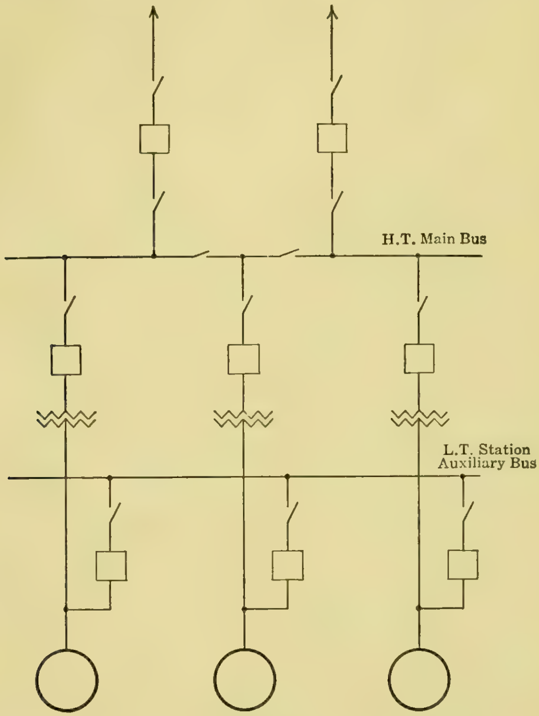


Fig. 324.—Typical System of Connections.

more or less different from those of other installations. There are, however, certain fundamental systems of connections, and Figs. 324 to 329 will serve to illustrate a number of the more important and more commonly used arrangements.

With the arrangement shown in Fig. 324, the generator and transformer are treated as a unit, and the low-tension switching is thereby omitted. The station auxiliaries can be fed from any generator by means of the auxiliary bus. The system, however, is lacking in flexibility and should only be used in small stations where continuity is

not of prime importance, and where the first cost must be kept down to a minimum. In stations of this capacity it is usually preferable to provide, say, two transformer banks with a single-phase spare unit; but when generators are added from time to time, the arrangement as illustrated may be used.

In general, it is advisable in any installation to reduce the number of transformer banks to a minimum, thereby cutting down the number of high-tension circuit breakers required. Due consideration must,

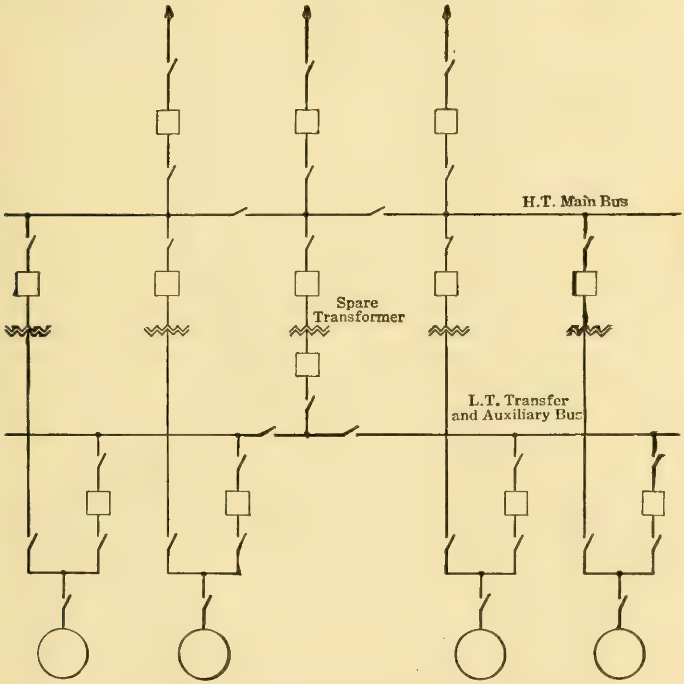


FIG. 325.—Typical System of Connections.

however, always be given to the operating conditions, so that flexibility and reliability are not sacrificed thereby. As stated above, at least two transformer banks should be provided with the necessary spares.

The system shown in Fig. 325 is also based on the principle of a generator and transformer forming a unit; and what was said regarding the previous scheme also applies in this case. The arrangement is more flexible than that of Fig. ~~303~~ 324, in that it permits any generator to feed any bank of transformers through the low-tension transfer or

auxiliary bus. A spare transformer can also readily be cut into service in case of breakdown to any of the other units.

To further increase the flexibility and reliability, a double high-tension bus can be provided, as shown in later diagrams.

With the connections shown in Fig. 326, the transformer banks are operated as units with the outgoing transmission lines; their arrangement

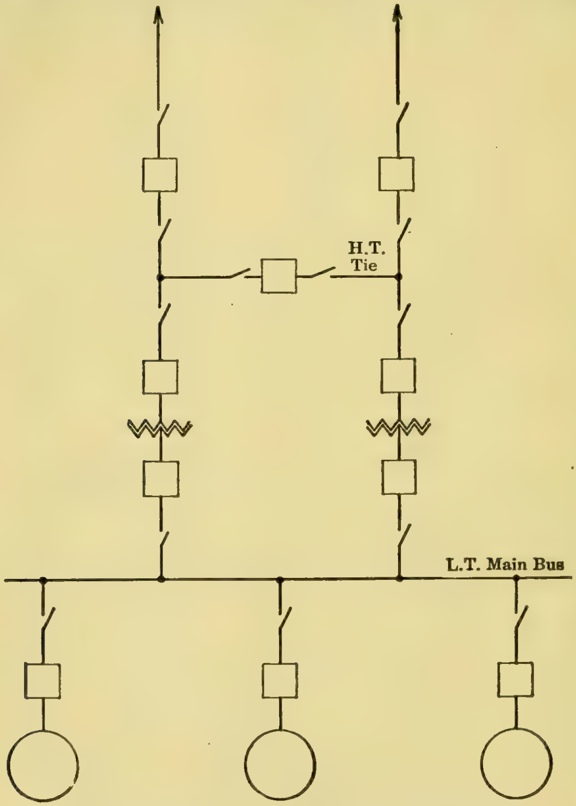


Fig. 326.—Typical System of Connections.

has been used extensively in the past and is primarily adapted to installations where the generating station supplies power to a single substation over a number of parallel lines. A disconnecting switch can be substituted for the oil circuit breaker in the high-tension tie-connection, and it is also possible to use disconnecting switches in place of the high-tension oil circuit breakers In the latter case, it would, of course, be impossible to provide differential protection for the transformer banks. With more than three lines, it is generally preferable to install

a regular high-tension transfer bus, arranged on the same principle as the low-tension transfer bus in Fig. 325.

The arrangement shown in Fig. 327 permits the operation of any number of generators, transformer banks and outgoing lines, and is undoubtedly the most commonly used system of connections. It gives great flexibility of operation with minimum cost, and is suitable for medium-sized plants. Buses are provided for parallel operation on both the high- and low-tension sides of the step-up transformers, and by installing sectionalizing switches in these buses, the station may be operated in separate independent units, if desired.

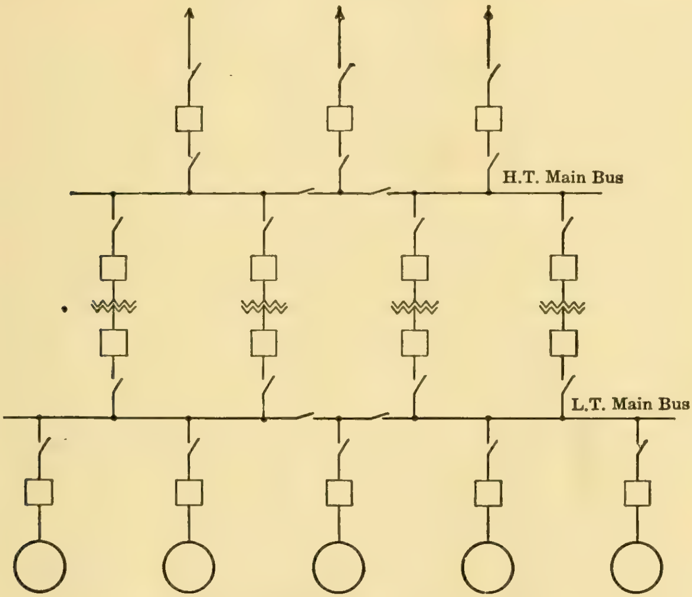


FIG. 327.—Typical System of Connections.

All single-bus systems are open to the objection that any failure of bus insulators, etc., may cripple the operation for more or less prolonged periods while repairs are being made; where continuous operation is necessary, it does not generally permit of periodically cutting out a section for cleaning and inspection.

The arrangement shown in Fig. 328, with a complete duplication of oil circuit breakers, disconnecting switches and busbars, will naturally assure the greatest flexibility of operat on, as well as the most complete insurance against prolonged shut-downs caused by bus or circuit-breaker failure. On account of expense, it is, however, only justified

in the very largest stations where prolonged interruptions must be prevented at any cost.

By reducing the number of oil circuit breakers and providing single breakers with selective disconnecting switches, while still maintaining double low- and high-tension busbars, as shown in Fig. 329, the first

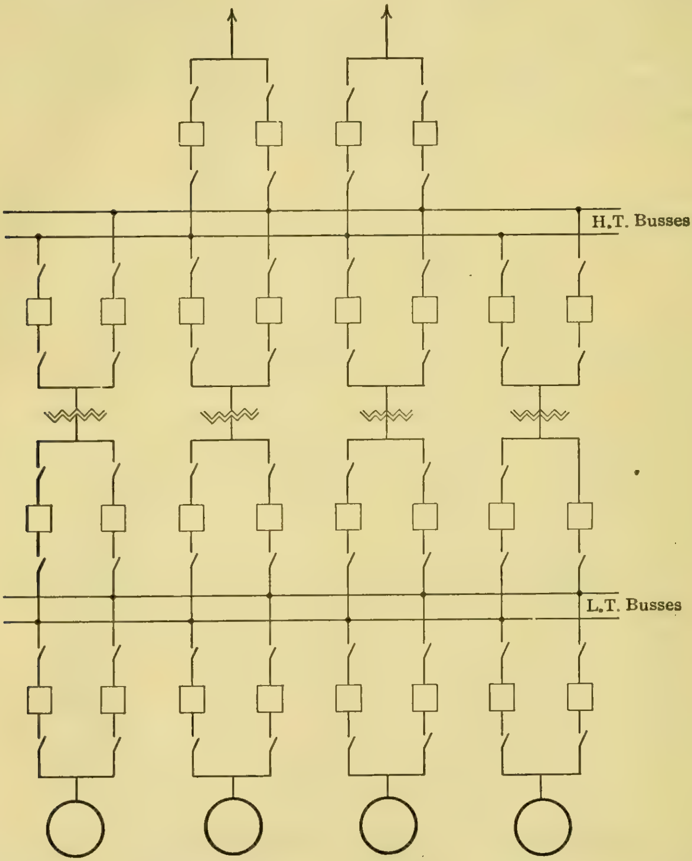


FIG. 328.—Typical System of Connections.

cost can be considerably reduced; but this, of course, can be done only at the sacrifice of the complete flexibility of operation which the scheme shown in Fig. 328 made possible.

With large stations, the main buses are, as a rule, divided into one or more sections, by means of disconnecting switches or oil circuit breakers. This is particularly true in the case of the low-tension buses, and reactors are often inserted between the bus-sections in order to

limit possible short-circuit currents to values which the apparatus can safely withstand and rupture.

This subject has already been treated under "Current-Limiting Reactors," and Figs. 308–310 were given to show different bus and sectionalizing arrangements.

Oil Circuit Breakers. The selection of the proper type and size of oil circuit breaker to meet the required conditions for which it is

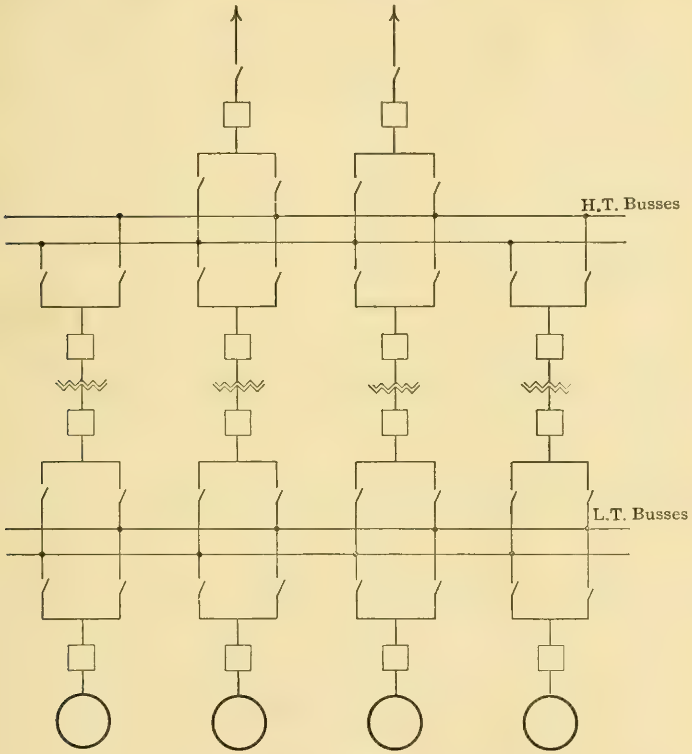


FIG. 329.—Typical System of Connections.

intended is of utmost importance, in order to assure a safe and reliable operation. This is especially true with present-day systems, which have grown in size, necessitating elaborate and complicated switching arrangements.

The application of the proper oil circuit breaker, therefore, involves a thorough knowledge and careful study of the operating conditions of the system as a whole and of the characteristics of the many apparatus involved. Among the requirements determining the type and capacity

of breaker to be used, the following are the most important: voltage, normal current capacity, short-time current capacity, interrupting capacity, safety features, methods of operation, whether for indoor or outdoor operation, arrangement of terminals, space required, adaptability to a particular arrangement, and other requirements which may be necessary for the particular case under investigation.

There is now such a great variety of oil circuit breakers on the market that standard breakers can, as a rule, be found to meet almost all requirements. Standard breakers should obviously be selected wherever possible, because of the lower initial investment and the ease with which parts may be replaced and interchanged. In some cases it may be necessary to select a breaker with a slightly higher rating than that required for the circuit at the time the selection is made. This should, however, not be considered a disadvantage, for in many cases it is found that the circuit or system capacity will soon have to be increased requiring this higher circuit breaker rating; and the expense of replacement is thus saved.

According to the A.I.E.E. Rules, the rating of an oil circuit breaker should be based on the following:

(*a*) The normal R.M.S. current which it is designed to carry.

(*b*) The normal R.M.S. voltage of the circuit on which it is intended to operate.

(*c*) The normal frequency of the current.

(*d*) The R.M.S. current at normal voltage which it can interrupt under prescribed conditions at stated intervals a specified number of times.

Oil-circuit-breaker ratings are generally based on the maximum current which the breaker is designed to carry, regardless of whether it is for normal continuous operation or on one or two hour overload bases. Under this condition, the maximum observable temperature rise of the various parts, according to the A.I.E.E. Rules, shall not exceed the following limits with an ambient temperature not greater than 40° C.:

Contacts	30° C.
Oil	40° C.
Series and Potential Coils, Class A Insulation	50° C.

The dielectric test for breakers above 600 volts should be $2\frac{1}{4}$ times rated voltage plus 2000 volts. As a supplementary test, the A.I.E.E. Rules specify that outdoor devices must be capable of withstanding for ten seconds a dielectric wet test at twice rated voltage plus 1000 volts. This assumes a precipitation of one-tenth inch per minute at an

angle of 45° from the perpendicular, with water having a resistivity as low as 7000 ohm-centimeters.

In selecting the proper type of breaker to use for a certain case, it is not enough to ascertain that the breaker has a sufficient current-carrying capacity or that it is capable of withstanding the operating voltage. The amount of power which the switch may be called upon to rupture under abnormal conditions, such as a short circuit, is a very important matter and deserves the most careful attention.

The interrupting capacity of an oil circuit breaker is the highest current in R.M.S. amperes which the breaker will interrupt at any specified normal voltage, frequency and duty. The interrupting of a circuit a specified number of times at a given current and pressure determines the *duty* imposed upon the breaker. The breaker interrupting capacities, in R.M.S. value of amperes, can be obtained from the circuit breaker manufacturer, and these values are generally based on an assumed duty, i.e., that the breaker will interrupt this value of current twice, at a two-minute interval, and then be in condition to be closed and carry its rated (normal) current until it is practical to inspect it and make necessary adjustments.

The rating of an oil circuit breaker, in R.M.S. current interrupted at normal operating pressure, simplifies the selection of a proper breaker for a given service condition. In the A.I.E.E. Rule establishing this rating, it is qualified by the words "prescribed conditions." It is generally recognized, and is indicated by test and by the operation of circuit breakers in service, that the power factor and the stored electrostatic and magnetic energy of the system are among the conditions affecting the interrupting capacity at a given R.M.S. current. During the current-opening periods, an arc is established, and the current and voltage relations during this period are much more complicated than the simple phase-angle relation covered by the statement of power factor. Furthermore, the arc may be re-established under transient voltage conditions, still further complicating the phenomena. The theoretical and empirical data available on the effect of these conditions on the work done by the breaker are not at present adequate to prescribe any particular power factor for test, nor to suggest any method for general use, to take into account the power factor and energy storage characteristics for all systems. These variables are taken into account, in a general way, in the factor of safety employed in the rating of a breaker, and their effects need not be considered in ordinary individual problems.

In general, a determination of the magnitude of current rushes, the R.M.S. current that will flow at the instant the contacts part, and

the lapse of time from start of short circuit to parting of breaker contacts, irrespective of power factor or circuit conditions, will enable one to select the proper circuit breaker.

In order to determine the R.M.S. current that the circuit breaker will be required to open, an analysis of short-circuit phenomena in the alternating current network would be necessary. The procedure to follow in making these calculations has already been described in the section on "Current Limiting Reactors," page 481.

It is not enough for a breaker to carry its normal load and to interrupt the short-circuit current; it must also be able to withstand the maximum heating and magnetic stresses imposed. The maximum initial R.M.S. rush of current, as determined from Table L, page 483, must not exceed the rated one-second short-time current capacity of the breaker; and the current which the breaker is required to carry before tripping under abnormal conditions must not exceed the one- and five-second ratings specified by the manufacturer for these respective time intervals. The short-time current-carrying capacity of the series trip coils, where such are used, may be the determining factor in selecting a breaker.

Under-voltage relays and under-voltage devices, when used, are important in determining the duty imposed on oil circuit breakers. When the total time of parting the breaker contacts tripped with an under-voltage device or relay is less than the total time of breaker and overload relay, this lesser value should be used in making oil circuit breaker selections. The above may be disregarded when it is positively known that the voltage will be sustained, in case of a short circuit, to such a value that the under-voltage device or relay will not drop out.

Oil circuit breakers are generally classified according to the method of mounting and the method of operation. Besides this, a particular class may cover several distinct lines or types with different rupturing capacities. The following classification will give the reader a general idea of the arrangements mostly used. The limitations given must only be considered as approximately representing present practice, and may naturally vary somewhat with the design and standards of the various circuit-breaker manufacturers.

(*a*) **Breakers are Mounted on Back of Panel (Manually Operated.)** When used with small plant boards, for circuits up to and including 2500 volts, when the breakers do not exceed 800 amperes.

(*b*) **Breakers are Mounted on Panel Frame (Manually Operated).** When used with large switchboards up to and including 2500 volts, also for any panels with breakers above 800 amperes. This mounting

should not be used when the greater number of the circuits to be controlled from the switchboard require breakers 800 amperes or larger.

(*c*) **Breakers are Mounted on Framework Remote from Panel (Manually or Electrically Operated).** 1. When used on circuits above 2500 volts up to and including 6600 volts.

2. When the greater number of breakers have a normal current capacity 800 amperes or over. However, when only one or two breakers are 800 amperes or larger and quite a number are of lower rating, all breakers should be mounted on panel frame.

3. When breakers are double-throw, except in occasional cases where connections can be made satisfactorily for breakers mounted on back of panel or on panel frame.

4. When breakers are of the large tank type up to and including 73,000 volts.

(*d*) **Breakers are Mounted in Cell Remote from Panel (Manually or Electrically Operated).** When circuits are above 6600 volts and the oil circuit breaker is suitable for cell mounting.

(*e*) **Breakers are Mounted on Floor (Manually or Electrically Operated).** When breakers are of the large tank type, above 73,000 volts. Structural iron framework may, however, be used.

Small or medium-sized oil circuit breakers are usually operated manually by means of a lever mounted on a panel, pedestal, or on the breaker. It is impracticable, and in many cases impossible, to operate large circuit breakers by this method, because of operators' inability to close the contacts without excessive mechanical leverage or to close the breaker fast enough when synchronizing. For positions a great distance away or inaccessible from the panel, or in the cases involving complicated operating mechanisms, manual operation should not be used.

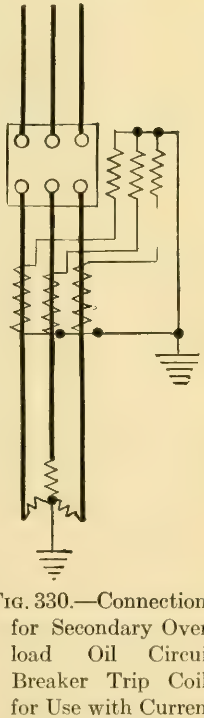


Fig. 330.—Connections for Secondary Overload Oil Circuit Breaker Trip Coils for Use with Current Transformers.

Very small manually operated breakers may be equipped with series trip coils located at the operating lever, and any time delay is then secured by the use of oil dashpots on the trip coil plungers. Usually, however, automatic tripping is accomplished by means of current transformers and secondary trip coils located at the operating lever, Fig. 330. With larger sizes of manually operated, remote-control breakers, the automatic features are at the

breaker, thus relieving the operating lever, bell cranks and interconnecting pipes from strains when the breaker is in the closed position.

Where the trip coils are located at the breaker, secondary relays mounted on the switchboard offer many advantages. In this position a relay is readily accessible and adjustments can easily be made. Relays are inherently more accurate than trip coils and may be obtained to operate to meet almost any requirement, while trip coils are usually limited to plain overload, either instantaneous or with time-delay. Relays also impose a lower volt-ampere load on the current transformers than trip coils. The subject of secondary relays is treated fully in the next section.

Automatic, manually operated breakers cannot be held in the closed position on overload. The operating mechanism at the breaker is so designed that the breaker trips free from the closing mechanism; hence, the operating lever must be brought to the full open position before the breaker can be reclosed by this operating lever.

Operation by means of electric solenoid or motor is considered standard for power-operated breakers. Standard solenoids (for tripping as well as for closing) are for direct-current operation. The solenoid method of operation permits mounting the operating mechanism on cell walls, on pipe frames and on the floor below (or above) the breakers. The operation of the solenoids is usually controlled at a remote point by a pull-button control switch. On account of the large amount of current taken for the closing coil, the control switch operates a control relay, which in turn closes the main solenoid circuit. Direct-current solenoids are available for closing the breakers at 90 to 140 volts and for opening the breaker at 70 to 140 volts, for 125-volt solenoids; and for closing the breakers at 180 to 280 volts and for opening the breaker at 140 to 280 volts, for 250-volt solenoids.

Electrically operated automatic breakers, whether motor or solenoid operated, are tripped by use of relays which complete the tripping circuit to the control bus. They are also arranged for manual operation in case of emergency.

A motor-driven centrifugal device has recently been developed for closing circuit breakers. It makes use of centrifugal force in a manner similar to that of a governor on a turbine, and will close any circuit breaker now using the standard universal lever for manual operation. The motor may be either alternating or direct-current, and is therefore particularly adapted to the operation of breakers in localities where no direct current is available. The motor revolves a pair of weights attached to the motor shaft, thereby developing a centrifugal force which tends to throw the weights outward and causes the operating

mechanism to close the breaker. The motor current is controlled in the ordinary way, by a control switch or a relay.

A good mineral oil should be used with circuit breakers. It should have a high ignition point and resistance to carbonization. It should also withstand the same insulation tests as specified for transformer oil.

From what has been previously said, it is evident that there must

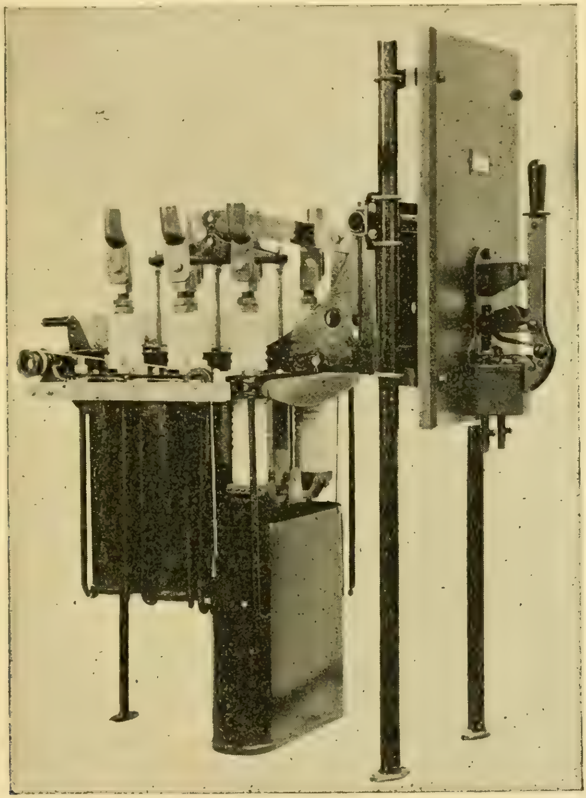


FIG. 331.—Three-pole, Single-throw Oil Circuit Breaker, 15,000 Volts, 800 Amperes; Mounted on Panel Frame.

be a very great variety of oil circuit breakers to meet the many different conditions and requirements. To describe them all would be impossible, and only a few representative types will be briefly dealt with in the following paragraphs.

Figure 331 represents a type of breaker which is recommended for moderate-capacity systems and for voltages up to 15,000. It can be mounted on the pipe frame supporting the switchboard panels, on

framework remote from the panel or in cells, depending on the ampere capacity and the voltage. It may be manually operated from the switchboard by means of operating rods, through a system of bell cranks, or electrically by means of a solenoid controlled from the switchboard.

The breaker consists of single-pole units attached to a frame. The main contacts are of a modified brush-leaf double-break construction. Secondary contacts and easily renewable arcing tips are provided, as shown in the unit with the tank removed. The wiping motion, when the main contacts are closed, insures a clean contact surface. The oil vessels are nearly elliptical in cross-section, and are of heavy sheet steel lined with pressboard to protect the tank against the action of the arc. Supporting rods, hooking at the bottom of the tank and extending through the frame cover above, hold the tank firmly in position. To facilitate the removal of the oil tanks, a tank lifter may be used. The insulating bushings generally consist of wet-process porcelain extending below the level of the oil.

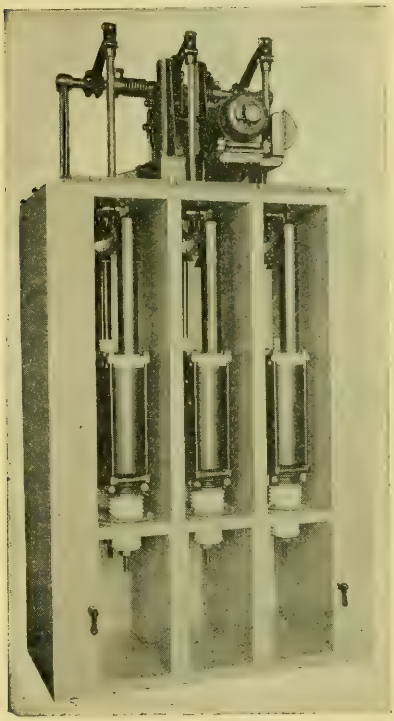


Fig. 332.—Type FH., Motor-operated Oil Circuit Breaker. Three-pole, 15,000 Volts, 500 Amperes.

The motor-operated oil circuit breaker, illustrated in Fig. 332, generally known as type FH, is intended for vo tages up to 35,000 and currents up to 4000 amperes, and for very high rupturing capacities. Each pole is made up of two separate seamless steel vessels, in each of which the circuit is broken under oil. These oil vessels can readily be removed for inspection and repairs. The top bushing is of porcelain and is securely fastened to the cover, which is screwed to a tight fit into the top of each oil vessel. The bottom bushing is also of porcelain and is fastened to the base supporting the oil vessel, by means of a metal clamp which holds it in proper alignment.

The circuit is broken at the bottom of each oil vessel, thus providing

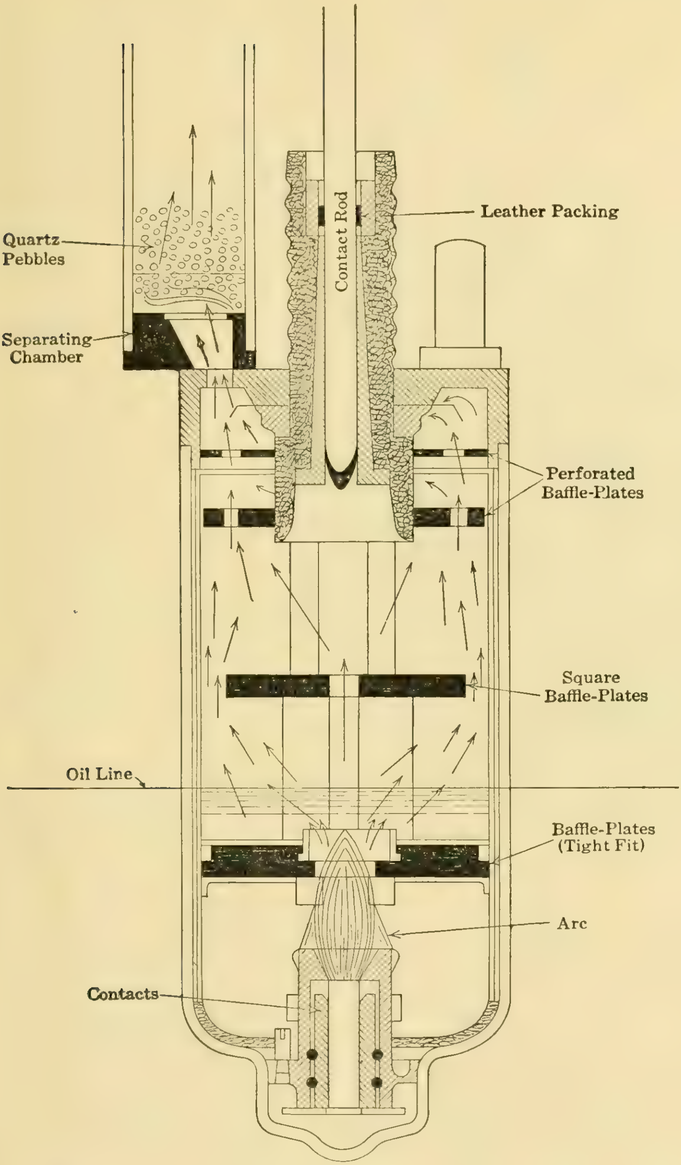


FIG. 333.—Diagrammatic Sketch Showing Path of Gases in Oil Tank of Type FH. Oil Circuit Breaker.

for a double break for each phase. A movable, round, brass rod enters a hollow cylinder consisting of vertical segments held together by springs. This arrangement insures a heavy and uniform contact pressure and automatically compensates for wear on the surface of either contact rod or contact segment. Upper contacts are provided for breakers of 500 amperes and above. These may be of the laminated brush type or the contact-finger construction, depending on the current to be carried. They close with a wiping motion against bosses or wedge-shaped copper blocks on top of the oil vessel covers, and from the main current-carrying parts, leaving contact before the inside lower contacts which break the arc. Bars on the outer sides of the oil vessel help to carry the current from the bottom clamps to the top contacts, and also serve to hold the top cap in proper position.

Figure 333 is a cross-section through one of the oil vessels, and plainly illustrates the baffle arrangement for preventing oil-throwing. The arc is interrupted below the lower baffle, and the gas which has been generated passes out through the center hole in the lower baffle, mixed with some oil spray. The gas and oil are partially separated while passing through the upper baffles, and are finally carried to a separating chamber (one for each oil vessel) filled with quartz pebbles, where a cooling of the gases takes place. The separated oil then returns to the oil vessel, and the gas is carried from the separate chambers, through a system of communicating pipes, to a general outlet. This outlet should be connected to a switch house header which should be piped outdoors, so that the gas will not be liberated in the station.

The above separating-chamber arrangement is a new feature in the design of this type of oil circuit breaker, making the breaker oil-tight and explosion-proof, the only outlet being through the separating chamber. The throwing of oil is thus entirely eliminated, as well as the danger of secondary explosion of the gas in the oil tank above the oil.

This type of breaker is always cell mounted and generally bottom connected, although it can be arranged for combined bottom and back connection. The cells should, of course, be made of some fireproof material, such as brick or concrete, preferably the latter. The cell doors are usually made of asbestos lumber panels with wooden frames.

The operating mechanism is located above the cell structure and connected to the contacts by operating rods of specially treated wood. Direct-current motor drive is recommended for use whenever possible, and when no other suitable source of direct current is available, a storage battery with motor generator for charging may be installed. (See "Oil Circuit Breaker Batteries.") Alternating-current motors can be furnished, if for any reason direct-current operation is not prac-

ticable. It should be borne in mind, however, that with alternating-current motor operation, a constant source of alternating current should be available, unless it is convenient to close by hand some oil circuit breaker, which would provide the necessary operating current.

Figures 334 and 335 show two oil circuit breakers from a line of breakers for use on systems of large capacity and operating at potentials from 15,000 to 154,000 volts. They are designed to meet a great variety of conditions of interrupting capacity, voltage and altitude, by assembling together different combinations of standard parts. For example, different interrupting capacities may be obtained by changing the size of tank and type of contacts, and the breaker can be adapted for installation at any altitude up to 10,000 feet, simply by selecting the proper type of bushing.

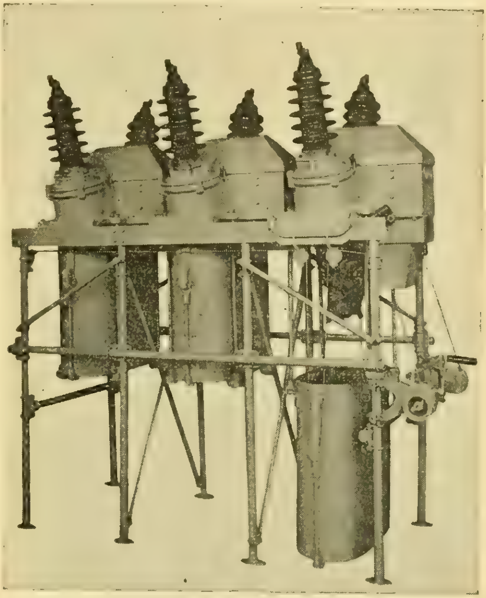


Fig. 334.—37,000 Volt Three-pole Solenoid Operated Tank Type Oil-Circuit Breaker; Frame Mounted.

As seen from the illustration, the breaker consists of single-pole top-connected units joined together by a mechanism and necessary bracing members. It may be used for either indoor or outdoor installation; in the latter case it is provided with a suitable hood for protection of the solenoid and mechanism from the weather. Breakers up to and including 73,000 volts may be either mounted on the floor or on a framework, provided there is sufficient voltage clearance above the breaker. This arrangement permits the tanks to be lowered for inspection and repair of contacts. For breakers above 73,000 volts, floor mounting is generally recommended, and such breakers are usually provided with manholes, so that, when the oil is removed from the tanks, a man can enter them for inspection and repairs. If the breakers are set on the floor, they should be mounted on suitable concrete supports, to allow sufficient ventilation under the tanks and enough space to permit painting the bottoms of the tanks.

The bushings are mostly of the interchangeable type, as used with transformers, etc. For breakers above 73,000 volts, they are filled with an insulating oil, while for 73,000 volts or less, they are of the solid-core type. A description of their construction will be found in the section on "Transformers."

The contact arrangement depends on the interrupting capacity of the breaker. For the lower interrupting values, they consist of drop-forged copper fingers secured to a contact block fastened to the terminal rod at the lower end of the bushing (Fig. 309). The movable contacts consist of a wedge-shaped bridging connected to the operating mechanism above the breaker by a specially treated wooden rod. Above 73,000 volts, static shields surrounding the contacts are also provided.

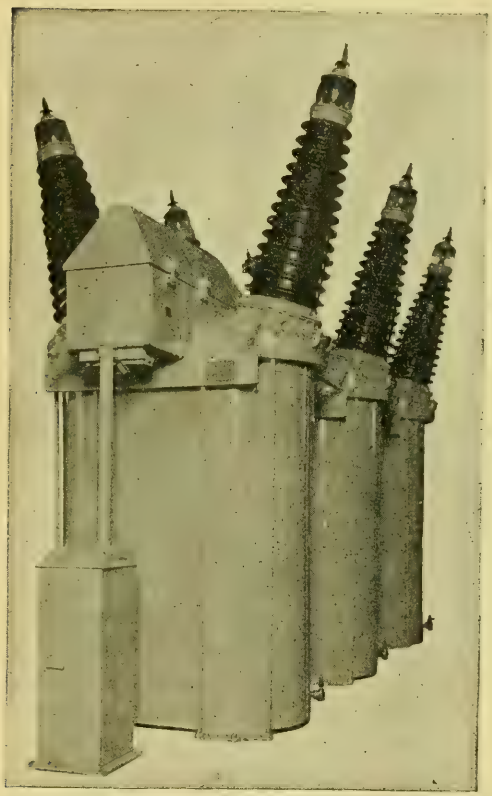


FIG. 335.—154,000 Volts, Three-pole Solenoid Operated Oil-circuit Breaker. Floor Mounted.

For high rupturing capacities, the explosion chamber construction, such as shown in Fig. 336, is used, the spacer between the bushing and the contacts being omitted for moderate capacities. The object of this spacer is to place the contacts deeper in the oil, to increase the rupturing capacity. The movable contacts consist of vertical copper tubes fastened to a vertical wooden bridging member, the contact tubes being connected together by copper bars. The fixed contacts, which are located in the upper part of the explosion chamber, are hollow cylinders made up of vertical segments bound together by helical springs, the construction being somewhat similar to that used with the type FH breakers previously described. Insulating tubes then surround and insulate the explosion chamber.

The breakers may be either manually or solenoid operated, the latter method, of course, being essential for the larger sizes. The operating mechanism is mounted on the top of the breaker, and so arranged that it can be removed without disturbing any other part of the breaker. Manually operated breakers can be provided with instantaneous or inverse time-limit trip, operating directly on the mechanism at the breaker, which then opens by gravity, assisted by springs on the mechanism. The trip coils may be energized from current transformers or from a source of constant potential. Manual tripping is also provided for.

When the breakers are solenoid operated, the trip coils are omitted, and the breaker is held in the closed position by the mechanism at the solenoid. The tripping is then done manually or electrically at the solenoid.

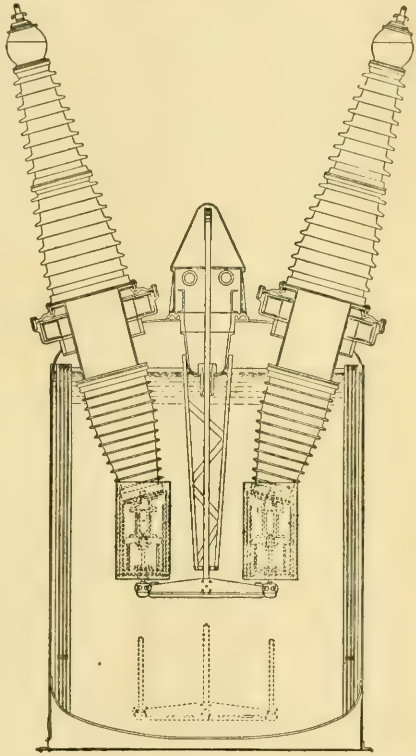


Fig. 336.—Cross-section of One Unit of 220,000 Volt Oil-circuit Breaker.

Figure 336 shows a cross-section of one of the units of the largest oil-circuit breaker so far constructed, its rated capacity being 600 amperes at 220,000 volts, with an interrupting capacity of 1,500,000 kv.a. It belongs to a line of breakers designed for very high rupturing capacities, and while its construction in general is quite similar to the line of breakers previously described, the increased rupturing capacity has been obtained by making the tanks of a round and exceptionally rugged design.

Relays. The proper functioning of a system depends upon the proper selection and application of its protective relays, which work in conjunction with the other protective apparatus on the system. The secret of success in relay protection is speed; that is, the faulty sections should be cut out so rapidly as to prevent injurious heating due to short circuits or heavy overloads, and also to prevent the synchronous apparatus connected to the system from falling out of

step. The time limit for this differs, however, depending on the stability of the apparatus and the location of the short circuit. The closer to the machines, the shorter the time before they drop out.

The longer an arcing ground hangs on, the more damage it will do in breaking insulators and melting off the transmission wires. The arc is very small to begin with, but increases rapidly in size and should therefore be quickly cleared so as to cause as little damage as possible.

Interruptions can, in many cases, be traced to the customer's own fault. For example the motor breakers may be set at such low-tripping value, that if the power of the system should momentarily drop off and come on again, the heavy current rush would trip the breaker and disconnect the machine. To provide against such interruptions the breaker need, of course, only be set for a sufficiently high value. The same thing occurs with motor breakers provided with low-voltage releases, which would cause the motor to be cut off from the system on any momentary voltage drop unless provided with a time-limit device. Such devices should therefore be avoided as far as possible, if strict continuity of service is essential.

The time in which a fault might be cleared depends naturally on how quickly the switches may disconnect the faulty section. This, in turn, depends on the rapidity of the switch action, and on the characteristics of the relay which is used for closing the tripping circuit of the oil circuit breaker, and on the safe rupturing capacity of the breaker. Owing to the inertia of moving parts, it is, of course, impossible for a circuit breaker to open absolutely instantly, and, as explained in the section on "Oil Circuit Breakers," it requires anywhere from 0.1 to 0.4 second for a breaker to open, the exact time depending on the type of breaker and actuating relay. During this time interval, the value of the short-circuit current will materially decrease, and relays may therefore also be used for the purpose of reducing the burden imposed on oil circuit breakers in rupturing heavy short-circuit currents. By the use of overload relays in connection with directional or differential relays, the characteristics and uses of which will be described in the following, it is possible to obtain a selective automatic switch action, which will only disconnect the faulty section of the system without interrupting the remainder thereof.

The choice between the different types of relays, as well as the choice of the best arrangements and settings to accomplish the desired result, depends entirely on the system of connections, the characteristics of the apparatus involved and the operating conditions. A solution of the problem requires, in the first place, a diagram of the system connections, such as previously described, giving the location and arrange-

ment of the synchronous apparatus, oil circuit breakers, transmission lines, etc. With such a diagram and the characteristics of the various apparatus involved, a comprehensive study of the short-circuit possibilities should be made, as described in the section on "Short-Circuit Calculations," page 481. Knowing these short-circuit values at different parts of the system, it is possible to begin the application of the relays for each particular circuit breaker, and to determine what settings the different relays should have, in order that they may function in the proper time and order. This matter of relay-settings is a very difficult problem, and will always require more or less readjustment before the relay-layout as a whole will function properly, especially on large and complicated systems. In fact, a change in the load at one point, or a slight change of the connections, may entirely upset the conditions and necessitate further adjustments.

It has, in the past, been a general custom to leave the generators entirely unprotected, and the generator circuit breakers have therefore been made non-automatic. This is still the practice in small stations. A. C. generators are, as a rule, of such sturdy construction that they can withstand a short circuit at the terminals without damage, and should therefore not need overload protection. It is furthermore argued that with the generator breakers provided with overload protection a severe short circuit on any outgoing line may cause all the generator breakers to trip out, thus unnecessarily shutting down the whole station.

In connection with the many large and expensive generators which have been installed during the past few years, it has been realized that some means should be provided to rapidly disconnect them from the rest of the system in case of internal troubles. This is preferably accomplished by a differential relay (as described in more detail later), which will instantly open the generator breaker and disconnect the machine from the bus, if, for any reason, trouble develops within the generator itself. Provision should then be made that the opening of the generator breaker will also automatically open the generator field switch, thus "killing" the generator entirely. This method of generator protection is now recommended for all synchronous generators 5000 kv.a. and above.

Although transformer banks are not usually protected against through shorts, they are generally protected against internal shorts by differential relays like the generators just described. In case of internal phase-to-phase short circuits or phase-to-ground shorts on grounded neutral systems, the relay will instantly open the high- and low-voltage circuit breakers and thus disconnect the damaged bank without interfering with the operation of the other banks.

For protecting outgoing lines, the simplest case would be single radial circuits feeding individual substations or loads, in which case the circuit breakers of these lines need only be provided with plain time-limit over-current relays. With several substations in tandem, the relays would be applied to the circuit breakers at the transmitting end of each section, and successively, with increasing time increment, from the most remote section to the generating stations. This is, of course, to prevent any sections between the generating station and the sub-station nearest a " short " from being disconnected. As practically all circuit breakers now being manufactured can be made to open in, say, 0.3 second, successive relays can be given a time difference of one-half to one-third second and thus allow a sufficient margin of safety. One-half second is thus considered ample with induction-type relays, while for plunger-type relays three-quarters of a second is generally recommended.

Several schemes may be used for the protection of parallel lines. For example, with two or more parallel lines supplying power from a generating station to a sub-station or feeding power between sub-stations in one direction, very satisfactory selective results can be obtained with a combination over-current and directional relay scheme. The circuit breakers in outgoing lines are then provided with over-current relays, and the breakers at the other end of the lines, that is, the incoming lines at the sub-stations, are provided with directional relays. With trouble on one line, the flow of power will therefore be in reverse direction through the incoming line breaker of the faulty line; and with a lower time element for the directional relays than for the over-current relays of the outgoing line breakers, it is evident that the damaged line will be automatically disconnected without interfering with the other line. With several sub-stations in tandem, the current settings of the over-current relays for the outgoing line breakers should be identical with the selective settings previously described for the radial system, while the directional relays are all given the same short-time setting. The details of this scheme, as well as those of the other schemes that have been referred to in a general way, will be explained more fully later in this section.

With lines operating in parallel, and where power is likely to flow in either direction, the most popular and satisfactory schemes of protection seem to be those which depend on the balancing of the current or power, which normally is approximately divided, in some definite ratio in these separate parallel lines. This involves the use of differential relays or relays differentially connected, and any appreciable unbalancing of the current or power in the lines, occasioned by line

faults, would at once be reflected in the relay, thus disturbing its balanced condition and causing the proper breaker to be tripped.

Differential protective schemes may, as stated, be based on an unbalancing either of current or of power. While differential current schemes for parallel lines are thus used very extensively, and are very popular because no potential transformers are required, their use is, however, limited. In such cases, where the simple current balance is not desirable, the differential power method using directional relays can always be used.

With two single lines feeding a number of sub-stations in tandem, and with a tie-connection between the two last stations, we have what is known as a ring system. The arrangement and operation of the relays in such a case is similar to that of straight parallel feeders; and when trouble occurs and the defective section is disconnected, the system becomes radial until this line is cut into service again.

Split-conductor and pilot-wire protective schemes are occasionally used, but not to any great extent for hydro-electric transmission work.

With solidly grounded neutral, system protection for grounds is, of course, taken care of by the phase relays. However, where the neutrals are grounded through a comparatively high resistance, it is becoming quite common practice to provide a ground relay in the neutral lead of the current transformer secondaries. This relay will then be energized only in case of a ground on the system; it may be set for a much lower current value than the phase relays, and in some cases at a lower time value. Both over-current and directional ground relays have been successfully used, and with time and current grading in the same manner as the phase relays.

Classification. In order to avoid confusion and to provide a uniform way of identifying the great number of types of relays now in common use, the Standards Committee of the A.I.E.E. has recommended the following nomenclature:

Classification According to Functions

Electric Protective Relay. An electric protective relay is an intermediate device, equipped with contacts to open or close an auxiliary circuit, by means of which one circuit is indirectly controlled by a change in conditions in the same or other circuits.

Directional Relay. A directional relay is one that functions in conformance with direction of power, or voltage, or current, or phase rotation, etc.

Power-Directional Relay. A power-directional relay is one that functions in conformance with direction of power.

Note: This includes both uni-directional relays with single-throw contacts and duo-directional relays with double-throw contacts. The reason this name is preferred to "reverse power" is that the device is frequently used to function under normal directions of power. Furthermore, in some cases the normal condition of the system may permit power to flow in either direction. Relays for use in either alternating- or direct-current circuits are to be classed as power-directional relays.

Polarity-Directional Relay. A polarity-directional relay is one that functions by reason of a change in the direction of polarity.

Phase-Rotation Relay. A phase-rotation relay is one that functions by reason of a change in direction of phase rotation.

Current Relay. A current relay is one that functions at a predetermined value of the current. These may be either over-current relays or under-current relays.

Voltage Relay. A voltage relay is one that functions at a predetermined value of the voltage. These may be either over-voltage relays or under-voltage relays.

Power Relay. A power relay is one that functions at a predetermined value of watts. These may be either over-power relays or under-power relays.

Frequency Relay. A frequency relay is one that functions at a predetermined value of frequency. These may be either over-frequency relays or under-frequency relays.

Temperature Relay. A temperature relay is one that functions at a predetermined temperature in the apparatus protected.

Open-Phase Relay. An open-phase relay is one that functions by reason of the opening of one phase of a polyphase circuit.

Differential Relay. A differential relay is one that functions by reason of the difference between two quantities, such as current, or voltage, etc.

Note: This term includes relays heretofore known as "ratio balance relays," "biased," and "percentage differential relays."

Classification According to Application

Locking Relay. A locking relay is one that renders some other relay or other device inoperative under predetermined values of current, or voltage, etc.

Trip-Free Relay. A trip-free relay is one that prevents holding in an electrically operated device, such as a circuit breaker, while an abnormal condition exists on the circuit.

Auxiliary Relay. An auxiliary relay is one that assists another relay in the performance of its function and operates in response to the opening or closing of its operating circuit.

Signal Relay. A signal relay is an auxiliary relay that operates an audible or visible signal.

General Qualifying Terms

Inverse Time. Inverse time is a qualifying term applied to any relay, indicating that there is purposely introduced a delayed action, the delay decreasing as the operating force increases.

Definite Time. Definite time is a qualifying term applied to any relay, indicating that there is purposely introduced a delayed action, the delay remaining substantially constant regardless of the magnitude of the operating force. (For forces slightly above the minimum operating value, the delay may be inverse.)

Instantaneous. Instantaneous is a qualifying term applied to any relay, indicating that no delayed action is purposely introduced.

Notching. Notching is a qualifying term applied to any relay, indicating that a number of separate impulses are required to complete operation.

In order to avoid any misunderstanding, the Relay Standards Committee also gives the following definitions:

Differential Relay. Explanatory note. In a differential relay, the resultant force operating the relay may be obtained by mechanical, magnetic or electrical means. Thus a relay is described as a mechanical differential relay, a magnetic differential relay, or an electrical differential relay.

Percentage Differential. Percentage differential is a term descriptive of the operating characteristics of one class of differential relays, and indicates that the relay requires an increasing difference to cause operation, which difference will approach a definite percentage of either or both of the opposing quantities.

Pick-up Value. The pick-up value, expressed in current, voltage, etc., is the minimum value at which the relay will complete its function.

Drop-out Value. The drop-out value, expressed in current, voltage, etc., is the maximum value at which the relay starts to rest.

Balanced and Residual Currents. The currents in the several wires of a circuit are divided for convenience into two classes of components, " balanced " and " residual."

The "balanced currents" are those wholly confined to the wires of the circuit. Hence, their algebraic sum is zero at every instant.

The remaining components of the currents in the several wires, which exist under conditions other than perfect vectorial balance, are termed "residual." The sum of the residual components is the "residual current" of the circuit. It is equivalent to a single-phase current in a circuit having the wires in multiple as one side, and the ground as the other.

Mathematically expressed, the residual current is the vector sum of the currents in the several wires, while the balance currents are those components whose vector sum is zero.

In general, a relay consists of (1) a coil or series of coils, (2) a movable part, such as a plunger or revolving disc, and (3) a contact device.

The coil or system of coils (1) is generally connected to secondaries of current or potential transformers, in which case the current and potential coils are wound for a low value, usually 5 amperes for the current coil and 110 volts for the potential coil, although other values might be used if desired. These relays are termed secondary relays to distinguish them from primary relays, which are connected directly in the circuit controlled. When thus used in the primary circuit with low-voltage oil circuit breakers, they are generally in the form of series trip coils and are known as such. Series over-current relays mounted on post insulators are occasionally used on high-voltage circuits.

The travel of the movable part (2) is controlled by the relay coils.

The contact device (3) is actuated by the movable part, and controls the operating circuit, for instance, the trip coil of the oil circuit breaker to which it is connected.

The impedance of a relay coil is relatively small compared to that of an oil circuit breaker trip coil, and if a number of instruments and meters are connected to a current transformer their accuracies are naturally affected by the total load imposed on the transformer secondary, decreasing rapidly as the load rises above a certain point. Some oil circuit breaker trip coils have a high impedance, and meter combinations requiring considerable accuracy consequently should not be used in series with them. By interposing a relay, which cuts out the trip coils except at the moment of trouble, the total load can be very materially reduced. The relay, therefore, simply serves to control the tripping circuit.

Circuit-closing and Circuit-opening Relays. Relays may be either circuit-closing or circuit-opening, with one, two or three coil trip, depending on the number of phases and whether the neutral is grounded

or not. As noted from the diagrams, circuit-closing relays require a separate source of power, preferably direct current, for operating the trip coil, while for circuit-opening relay the tripping current is obtained from the secondary of the current transformers.

With circuit-closing relays (Fig. 337), the relay contacts are normally open and the trip coil is dead; but at the moment of operation contact is made, thus completing the circuit and energizing the trip coil, which in turn causes tripping of the breaker. With circuit-opening relays (Fig. 338) the relay contacts are normally closed and the trip coils

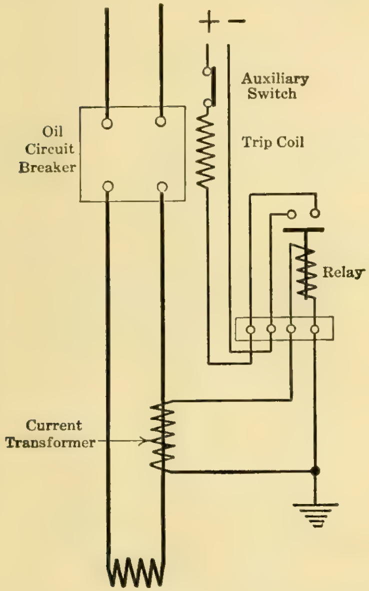


FIG. 337.—Connections of Single-phase Circuit-closing Relay.

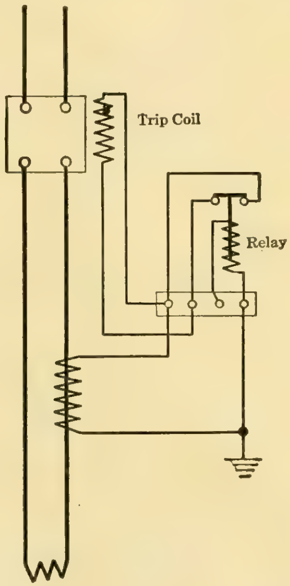


FIG. 338.—Connections of Single-phase Circuit-opening Relay.

de-energized, because under these conditions the current will take the path of least resistance through the contact blocks and not through the comparatively high-impedance path through the trip-coil winding. When a short circuit occurs on the main circuit, the contacts open and allow the current to pass through the trip coil, thus tripping the circuit breaker.

Circuit-closing relays are almost exclusively employed in connection with the circuit breakers used on large power systems, and circuit-opening relays only in those cases where direct current is not available. On account of the heavy secondary currents which are liable to flow

on severe short circuits and the comparatively high impedance of the trip coil, which may tend to hold up the voltage, a considerable arc is liable to be set up when the contacts are opened; and there is, therefore, a limit above which it is not safe to use circuit-opening relays. As a rule, they should not be used when the short-circuit current exceeds ten times the normal rating of the current transformer.

Tripping Reactors. Where direct current for tripping is not available, and circuit-closing relays must be used, tripping reactors are used, as shown in Fig. 339. The reactor is connected permanently in series with the secondary of the current transformer, and will have a potential built up across its terminals by the passage of the current. If the current is sufficiently high to operate the relay, it will be high enough to provide the necessary potential for the trip coil. Figure 339 shows a diagram of connections for a three-phase system with grounded neutral, one trip coil being recommended for each relay and, of course, one tripping reactor for each single-pole relay.

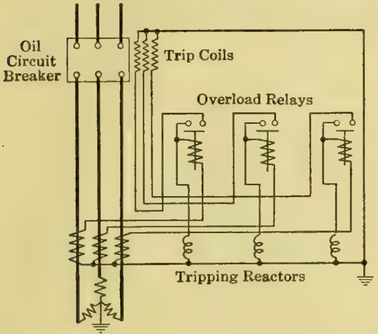


FIG. 339.—Circuit-closing Relays with Tripping Reactors.

When tripping reactors are used, the relatively large volt-ampere load which they impose on the current transformers must be considered, and in some cases separate current transformers for the reactors are required. It has been proposed to avoid the use of such additional current transformers by means of auxiliary, instantaneous, circuit-opening, plunger-type relays, with their contacts connected across the tripping reactor, the trip circuit being operated by a time-limit circuit-closing relay. This combination should not be used for two reasons. First, the introduction of the reactor in the current-transformer circuit may reduce the secondary current. Second, the drop-out value of the instantaneous relays mentioned is less than the pick-up value. As a consequence, a momentary overload might introduce and then leave the reactor in circuit, interfering with the accuracy of instruments and meters connected to the same current transformers, and remaining open at some value, say, between 3.5 to 5 amperes, thereby causing considerable instrument or meter inaccuracy.

Over-current Relays. These relays, which are also generally termed overload relays, may be instantaneous, definite time limit or inverse time limit. With instantaneous relays, the contact device will operate

immediately and close the tripping circuit of the breaker, when the abnormal conditions which the relay is to take care of make their appearance and start the moving part of the relay. With definite time-limit

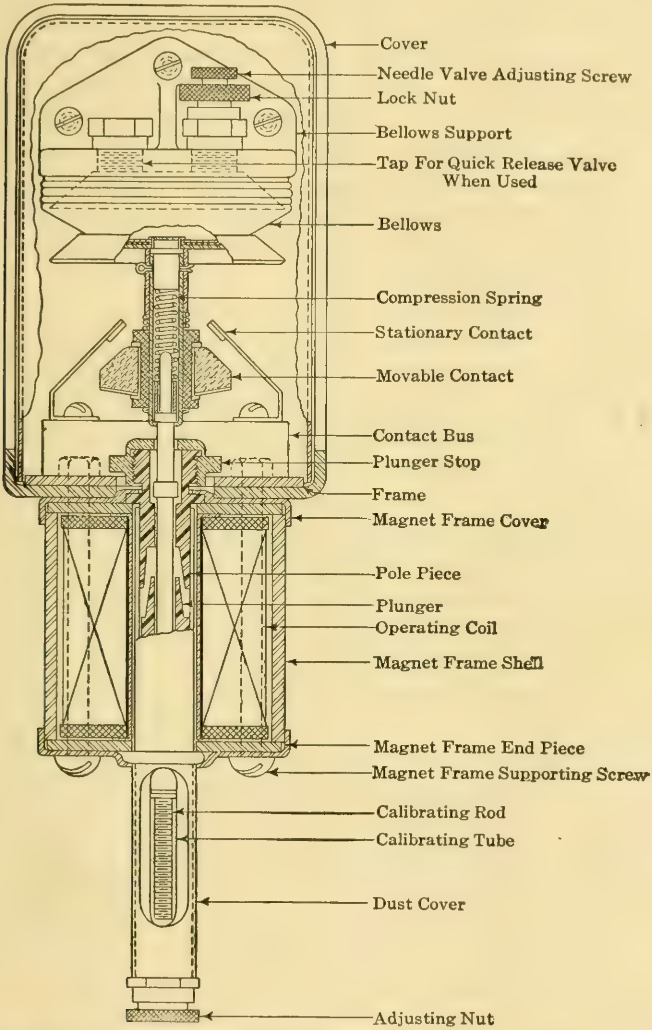


FIG. 340.—Plunger Type, Over-current, Circuit-closing Relay; Inverse Time Delay, or Definite Time Delay, or (when bellows is omitted) Instantaneous.

relays there is, as the name implies, a definite time delay imposed between these two moments, independent of the magnitude of the disturbance, and the time limit therefore becomes practically constant

for any given setting. With inverse time-limit relays the time delay is inversely proportional to the magnitude of the disturbance, so that with a heavy short-circuit it will be practically instantaneous for any time setting, while on a light overload the time may be several seconds, depending on the setting.

For instantaneous overload protection and for less important systems where few time gradings are required, the *plunger type relay* (Fig. 340) is satisfactory. It consists of a core or plunger, which is movable within a solenoid. When a sufficient current flows through this coil, the core is pulled up and, with the circuit-closing relay, a member mounted on the plunger rod bridges the gap between the contacts. With the circuit-opening relay, the opening contacts are of a quick-break toggle construction.

Time-limit relays of the plunger type are similar in general construction to those of the instantaneous type, except for the addition of an air bellows (Fig. 340) which limits the rate of travel of the relay plunger, thus introducing an interval of time to the opening or closing of the contacts. This time may be regulated, according to the nature of the service desired, by means of a needle valve.

On time-limit relays, a compression spring is interposed between the armature and the diaphragm of the air bellows. The contacts are actuated upon movement of the diaphragm. As the relay functions the plunger tends to compress the spring, which in turn reacts upon the diaphragm. For inverse-time-limit relays, this spring is stiff enough to resist compression except by heavy overloads. Thus the time delay is in inverse proportion to the overload. On very heavy overloads the spring is compressed quickly until the collar on the plunger rod reaches the stop at the top of the pole piece, and the movement of the diaphragm occurs upon expansion of the spring. The time delay in this case becomes a definite value. On definite-time-limit relays, the spring is much lighter and is compressed on an overload slightly above the current setting. Therefore, the time delay is definite for current 50 per cent or more above the current setting. The current setting may be varied by changing the position of the plunger in the coil. An adjusting nut at the bottom of the calibrating tube is provided for the purpose.

The current coils of standard plunger type relays are designed to carry 5 amperes continuously, and such relays are calibrated for 5, 8, 12 and 15 amperes. These values represent the minimum amperes in the relay coil which will lift the plunger and open or close the relay contacts. A needle valve provides means for the desired time settings, and the time delay with this type of relay can be adjusted within limits

of approximately 0.2 to 20 seconds, with 125 per cent of the minimum current at which the relay is to function. With an 8-ampere current setting, for example, this would correspond to 100 per cent current setting; but with plunger-type relays the time settings below the 125 per cent current setting value are not ordinarily taken into consideration, on account of the inaccuracies below this value.

The time of operation for which a relay is to be set must be decided with reference to the operating conditions involved, in order to obtain the protection desired against moderate or severe overloads. If selective action of two or more relays is required, it is necessary to determine the maximum possible short-circuit current of the line, and choose, for each relay, time values differing sufficiently to insure the necessary delay in the operation of each circuit breaker controlled by the relays in question. In this connection it should be noted that if the tripping time, as specified, refers only to the time consumed in operating the relay before the contacts open and close, an additional allowance must be made for the time element involved in the opening of the circuit breaker after the operation of the relay contacts.

The necessity of choosing time settings of sufficient difference at the greatest possible overload, in order to obtain selective action of relays, is readily seen by reference to the characteristic curves (Fig. 343). These curves refer to the induction-type time-limit relay which will be described shortly hereafter. The difference in time between the curves for two settings is least at the highest overload, and it is here that sufficient difference of time must be provided.

In order, however, to show how a relay may be set under particular conditions, let us assume that the relay in question should open a line breaker on the occurrence of sustained minimum overload of 500 amperes and should also open in one and one-half seconds on a maximum short circuit of 3750 amperes primary current, the current transformer ratio being 300 to 5. The current setting is then found by dividing the minimum primary current to open with the current transformer ratio. Thus,

$$\frac{500}{60} = 8.33,$$

in which case the 8-ampere current setting would be used.

The time setting should then be such as to give $1\frac{1}{2}$ seconds delay when $\frac{3750}{60} = 62.5$ amperes flows in the secondary circuit. This would, therefore, be a definite point on the time-current curve, and for lower current values the time delay would be correspondingly longer, according

to the curve for the particular relay involved, the curves being generally supplied by the relay manufacturer. The actual results should be checked with an accurate timing device, and the setting adjusted until the desired delay has been obtained.

Where several relays are involved and graded settings are required, it is preferable to begin with that which is to have the lowest time setting, which may be, say, one-quarter second. Then, the sustained current, as well as the short-circuit current, which the second breaker is to rupture is determined, and with the current transformer ratio given, the current setting for this relay is first determined, and thereafter the time setting, which may be three-quarters of a second with the secondary current, corresponding to the limiting primary short-circuit current, flowing in the relay coil. It is, as stated, important to select these time differences at the maximum current values. In the first place, they will be a minimum at these points, increasing in value as the currents decrease, while, in the second place, more accurate results are obtained the higher the current through the relay.

For large, important systems, where several time gradings are required to insure selective-circuit breaker action, the *induction type* over-current relay (Fig. 341) is recommended.

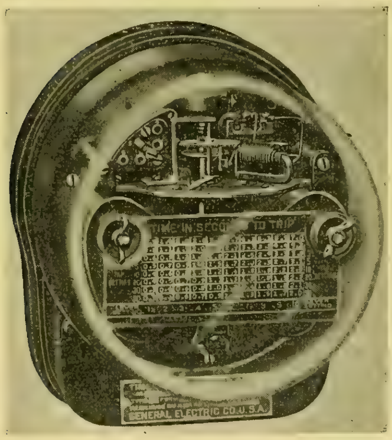


FIG. 341.—Induction Type Over-current Time Limit Relay.

The general principle of operation is as follows: when an overload occurs, the rotation of the disc, actuated by a "U" shaped driving magnet and retarded by a pair of permanent magnets, causes the contact tips to be forced together after an interval of time, which is dependent upon the amount of current, and upon the starting position of the disc, as predetermined by the setting of a time lever. The driving torque is generated by the phase-splitting action of shading coils on the pole pieces. The coil of the holding magnet is connected in series with the tripping contacts, causing this magnet to be energized at the instant the contacts close, and to attract and hold its armature, which is secured to one of the contact members. This holds the contact firmly closed until the tripping current is interrupted by a circuit-opening auxiliary switch

on the circuit breaker, thus preventing arcing or burning of the contact surfaces.

The relays are designed for use in the secondary circuit of current transformers, and the normal rating, or continuous current-carrying capacity, is 5 amperes. Taps are provided in the relay winding, and by inserting a metal plug in a current tap plate, settings 4, 5, 6, 8 and 10 amperes may be obtained, these figures representing the lowest current values required to close the relay contacts. Any tap setting, multiplied by the ratio of the current transformers, gives the corresponding primary or line current, and the ampere rating of the tap used must always be set above the secondary current which corresponds to the normal "full load" current of the line or machine to be protected.

A time-current index plate (Fig. 342) is provided as a guide for making time settings for any current calibration. The time values are given in seconds, and the time adjustments are made by a small lever, movable over a horizontal scale at the lower part of the plate and graduated from 0—10. This controls the time of operation by varying the starting point of the disc.

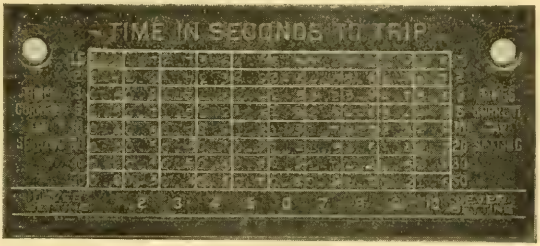


FIG. 342.—Index Plate for Induction Type Time-limit Over-current Relay.

The index plate bears 80 time values, at 1.5, 2, 3, 5, etc., times the ampere values of the current tap; that is, these values can be converted into actual amperes by multiplying them by the current tap setting which is to be used.

To illustrate, let us assume our previous example with a current tap setting of 8.33. We must, then, find the nearest "times current tap setting" on the index plate, which will be 10. Following the corresponding horizontal column, we find that 1.5 seconds delay will occur when the lever setting is half way between 6 and 7, and the lever should therefore be set at $6\frac{1}{2}$, to give one and one-half seconds delay.

In the above, the nearest whole number was used for "current tap setting"; this, of course, will mean that the time delay will be approximate. It will, however, be close enough for ordinary conditions, but not if the relay is to function with a very specific delay either before or after some other relay in the system which has been accurately set.

A curve should be drawn by taking values between the 5 and the 10 times current tap setting from the index plate and from this curve the proper lever setting may be found for the $7\frac{1}{2}$ times current tap setting. The results obtained from the above should always be checked with an accurate timing device, and slight movement of the time lever should be made until the desired delay has been obtained.

Figure 343 shows the characteristic time-current curves of the induction-type relay just described, with various time lever settings. It should be noticed that the curves are not given for values below $1\frac{1}{2}$ times the minimum or pick-up current, as below this value the results would be apt to be quite inaccurate and misleading.

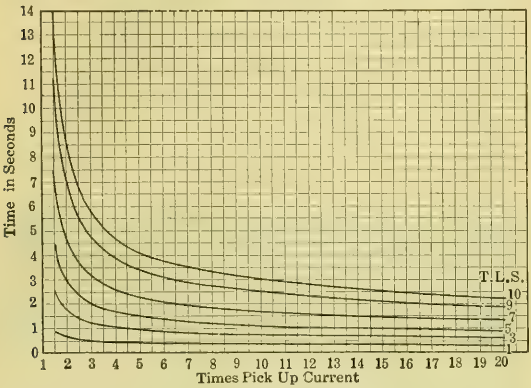


FIG. 343.—Time-current Characteristic Curves at Various Time-lever Settings with Induction Type Time-limit Relay.

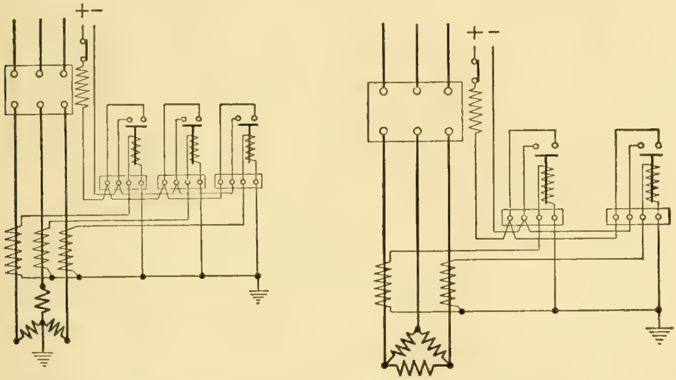
The operating or characteristic curves for various lever settings are entirely separate and distinct, even at the heaviest overloads, and never become instantaneous, although the time lever can be moved to a position lower than No. 1 setting, making the time delay approach instantaneous action. This is because of the inherent characteristics of the relay, which produces a curve consisting of an inverse time portion up to approximately 2000 per cent of minimum contact-closing current, blended into an approximately definite time portion with a slight downward slope. Consequently, the relay will do the work ordinarily required of both inverse and definite relays.

Over-current relays, whether of the plunger or induction type, are now only made in single-pole units, of which one, two or three are used, depending on the nature of the circuit to be protected.

Figures 344 and 345 give the fundamental connections of circuit-closing and circuit-opening relays for three-phase circuits both grounded and ungrounded.

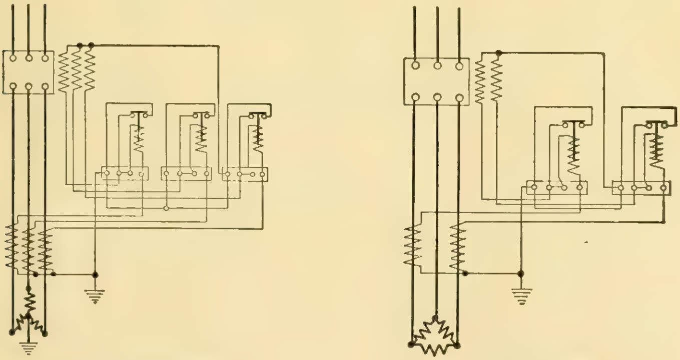
The simplest use of over-current relays is, as previously mentioned, in connection with the protection of *single circuits*, where the time settings can be graded successively, with increasing increment of time, from the most remote section to the power source.

Over-current relays, differentially connected, can be used for *balanced* protection of *two parallel* tie lines, with power normally flowing in either direction. This scheme, which is illustrated in Fig. 346, has the disadvantage of not affording any discrimination between the sound and injured, so that in case of fault in one line, both will be



(*a*) Grounded Neutral (*b*) Ungrounded

FIG. 344.—Connections of Circuit-closing Over-current Relays for Three-phase Circuits.



(*a*) Grounded Neutral (*b*) Ungrounded

FIG. 345.—Connections of Circuit-opening Over-current Relays for Three-phase Circuits.

disconnected temporarily until the sound line is found and replaced in service. Such a temporary interruption between the two stations may, in many cases, be permissible, as there is usually power available in either, and the inconvenience is partly offset by the freedom of potential connections. The scheme is. however, not generally used,

but will be described in order to give the reader an understanding of the principle of differentially connected over-current relays.

Referring to the diagram (Fig. 346), it is seen that, as long as the currents are equal and in the same direction in the two lines, no current flows through the relay coils. On a fault or short circuit in either line, there will at once be an unbalance between the currents in the two lines. The resulting difference in the currents is reflected in the current transformers, and a current flows through the relay coils, causing the contacts to close, and tripping both circuit breakers at each end of the line. The arrows in the diagrams clearly indicate the direction of the currents: *A*, under normal operation; *B*, with a restricted fault; and *C*, with a more severe fault, such as a short circuit. It is also evident that a short circuit at either bus, or beyond, will not cause the breakers to open, provided the line characteristics are such as to maintain a balanced condition.

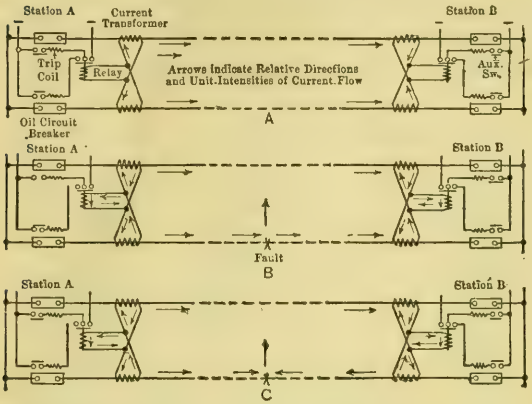


Fig. 346.—Balanced Current Protection for Two Parallel Tie Lines (not Discriminating.)

When the lines have been tripped on account of a fault in one line, the sound line should immediately be cut in again, the usual practice being to provide it with a time-delay overload protection. The connections to accomplish this are shown in Fig. 347. When the fault occurred the breakers were opened, through the action of the instantaneous relay; but the opening of the breakers

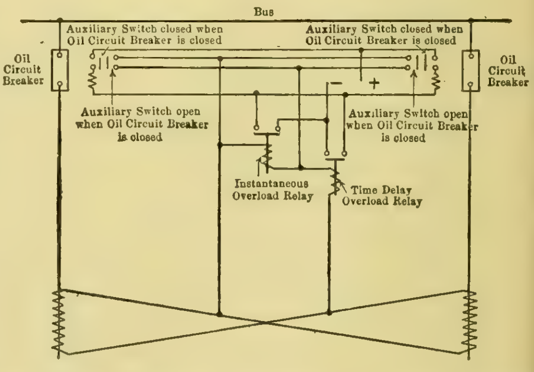


Fig. 347.—Balanced Protection of Two Parallel Lines with Time Overload Protection for Single Line Operation. (Not Discriminating.)

caused the auxiliary switches of the breakers in the faulty line to close, making the instantaneous relay inoperative and the time-delay relay operative on the closing of the breakers in the sound line.

Figure 348 shows how over-current relays may be used for *balanced current* protection of *three or more parallel* incoming, outgoing, or tie lines, without any potential connections. As long as there is a balanced condition with respect to the current on all lines, the relays will not be affected, and the breakers will stay in for all through short circuits. If, however, an unbalanced condition occurs, the majority of the circuits will control the minority, irrespective of whether the minority carries more or less current than the majority. Thus, if a fault occurs in one of the lines, it will be disconnected nearly instantaneously, regardless of whether it carries more or less current than the other sound lines. With this scheme, at least three lines should be in service to give selective action; and the more lines there are in circuit at

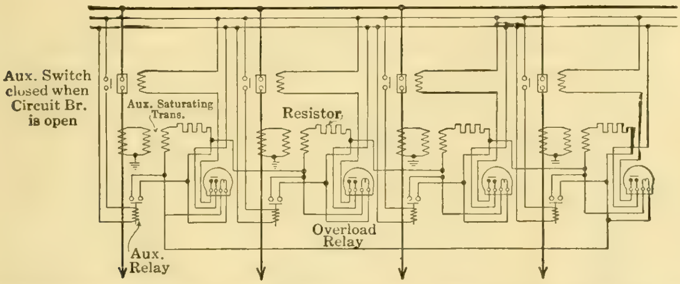


FIG. 348.—Balanced Current Protection for Three or More Parallel Lines.

any time, the more certain the operation of the equipment will be. When only two lines are left, both would open for trouble in either. When only one line remains in operation its relay equipment is short-circuited by the auxiliary switches of the circuit breakers in the other lines which are out of service. Such single lines would, therefore, have no protection unless the loop circuit were opened by means of a lever switch, which may be inserted for that purpose.

Saturating transformers are connected to the secondaries of the instrument transformers. They are used for two reasons, namely: to limit the amount of current which any individual line can furnish to the loop, and also to permit grounding each instrument transformer's secondary circuit close to the winding. The resistance connected in the secondary of the saturating transformer also assists in limiting the amount of current furnished to the loop. The secondaries of all saturating transformers are connected in series through the respective resist-

ors. An induction overload relay is then connected directly across each saturating transformer and its resistor. The auxiliary relay contacts, or the auxiliary switch on the oil circuit breaker, is connected across the protective relay circuit and is intended to short-circuit the relay and other equipment whenever the oil circuit breaker of that circuit is open.

With three or more parallel lines in operation, selective action can also be obtained by over-current relays, because, in the event of a fault in one line, the current feeding into this line would be materially greater than the current flowing through the others. To be reliable, this scheme would require relays with very inverse time characteristics, and it is no longer used to any great extent.

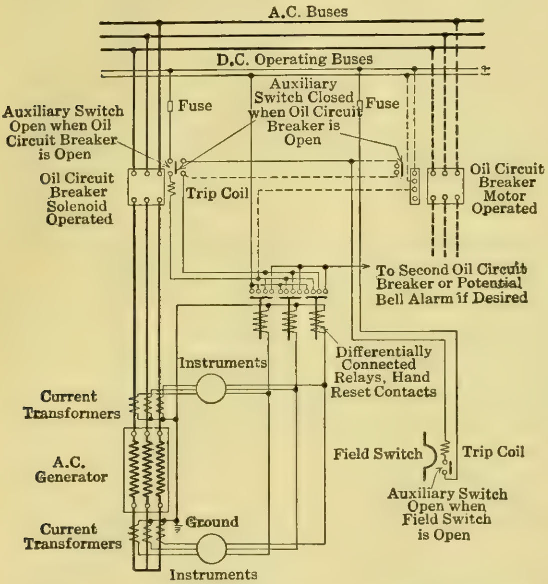


FIG. 349.—Connections of Instantaneous, Hand Reset, Overload Relays for Differential Protection of Y-Connected Alternators.

NOTE.—When a motor-operated oil circuit-breaker is used a special auxiliary switch to close immediately after oil circuit breaker contacts part is necessary to reduce time of tripping field switch to a minimum.

Alternating current generators are now generally protected from internal troubles by over-current relays differentially connected, as shown in Fig. 349. This is accomplished by bringing out the leads of the machine to be protected and inserting current transformers at both ends of the windings. The secondaries of the transformers of each phase are connected in series, and an over-current relay is connected in parallel with each pair of current transformers.

With the alternator running normally, the same amount of current flows in both current transformers of the same phase, and therefore no current flows in the coil of the relay. But, in case of an internal short circuit between phases or an internal ground (providing the neutral is grounded), an unbalanced condition would be set up; that is, a greater amount of current would flow in one transformer than in the other.

In such a case the unbalanced secondary current would pass through the relay and this would operate instantaneously to trip the breaker, if the unbalanced current should exceed the minimum operating point for which the relay is set. The contacts remain in closed position until manually reset. Since the currents are balanced under normal conditions, a sensitive setting of the relay is possible.

Provision should also be made for automatically opening the field circuit of the alternator after the oil circuit breaker has opened. This is desirable because a high voltage would be induced in the field winding in case the oil circuit breaker was opened when heavy current was passing through the armature.

If the field switch should be opened first, there is a greater possibility that the alternator would fall out of step with the remainder of the system, thereby increasing the disturbance on the system. If, for any reason, the main circuit breaker shou'd fail to open, it would be preferable to have the field switch also remain closed.

It is also possible to protect generators from internal troubles, when only the neutral is brought out and grounded, by balancing the vectorial sum of the currents in the three current transformers in the generator leads against the current in a single current transformer in the ground connection.

Protection of *power transformers* in case of internal phase-to-phase shorts, or phase-to-ground shorts on grounded neutral systems, is also very generally accomplished by differentially connected over-current relays, as is the alternator protection just described. This arrangement is, however, only feasible where it is possible to choose the current transformer ratios and connections so that under normal operation the resulting opposing secondary currents are equal in value and 180° apart in phase.

The ratio of power transformers is, however, usually such that equal values of secondary current cannot be obtained from current transformers of standard ratio on the high-voltage and low-voltage sides. Quite frequently taps are also provided in the windings of the power transformers, and the ratio used may be changed from time to time. Furthermore, if power transformers are connected delta-Y or two phase-three phase, the secondaries of one set of current transformers must be connected to give the resultant current in phase with the secondary current from the current transformers on the other side. This resultant current will differ in value from that of its components.

If, for example, the power transformers are connected in delta on the low-voltage side, and in Y on the high-voltage side, the secondaries of the current transformers on the high-voltage side must be con-

nected in delta to obtain current in phase with that from the Y-connected secondaries of the current transformers on the low-voltage side. The resultant current from the delta-connected secondaries will then be $\sqrt{2}$ times the current from each transformer.

In order to balance such unequal currents, the use of auxiliary auto-transformers in the differential connections is recommended. By means of taps in these auto-transformer windings, and proper connections, the smaller value of the current passes through a section of the coil, and the difference between the currents passes in an opposite direction through another section, the ratio of turns being inversely proportional to the current of lower value and the difference in current. In other words, counting the turns from the common end of the auto-

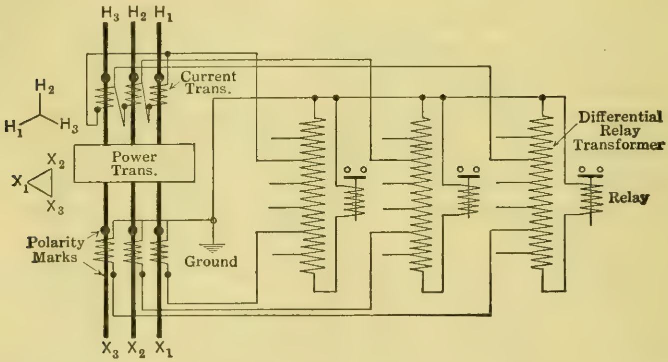


FIG. 350.—Differential Protection of Power Transformers Showing Use of Auxiliary Auto Transformers.

transformer winding, the taps used will represent any number of turns inversely proportional to the currents in the leads to the taps. This results in zero flux in the core of the auto-transformer under normal conditions, and in a flux representative of the changes in magnitude and direction of primary current if trouble occurs in the power transformer windings. The relay coil is connected across the end terminals of the auto-transformer and is affected correspondingly.

Figure 350 shows the connections for such a differential protective scheme, with power transformers connected delta low-voltage and Y high-voltage.

Directional Relays. Directional or reverse power relays, as they are also commonly termed, are used very extensively in power-transmission work. As the name implies, they operate on a reversal of power flowing in a circuit and are usually of the induction type, the principles of opera-

tion being in general similar to those of induction watt-hour meters. The torque is very high, while the power required to operate them is small. They are extremely sensitive and function at a very low voltage. While single-phase units may be had, the polyphase construction is generally used.

Polyphase relays (Fig. 351) are provided with three separate driving elements, each consisting of a current and a potential coil. The former has a normal rating of 5 amperes and the latter 110 volts, and they are thus intended to operate from the secondaries of current and potential transformers. Two elements work on one disc, and the third on a second disc, both discs being connected to a common shaft to operate the contacts. For systems with grounded neutral, one current transformer for each current coil is required, while for ungrounded systems two transformers are sufficient These are connected to two current coils, and the third current coil carries the resultant current of the two current transformers.

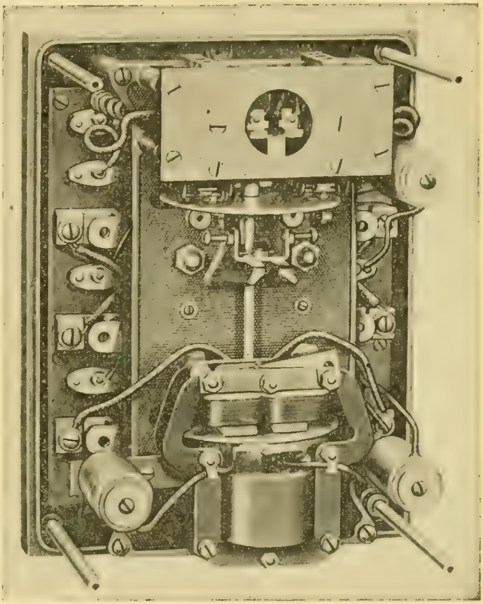


Fig. 351.—Polyphase Induction Type Reverse Power Relay. (Cover Removed.)

All these relays are made with circuit-closing contacts only, and operate instantaneously under usual conditions. Any time delay desired is provided by use of overload or auxiliary relays. Overload relays are required when protection for line faults is desired, generally for the purpose of preventing the tripping of a line until certain predetermined current values are reached. In the case of balanced lines they insure that neither line will be tripped unless the vectorial difference in current in the two lines is in excess of their current settings. An exact balance of currents in any two parallel lines is very improbable, if the lines are at all loaded; therefore, the sensitive reverse power relay is likely to have its contacts closed on the wrong side, even though both lines are in service, unless sufficient time is given the reverse

power relay to act before the tripping circuit is closed. The desired time is usually provided by the overload relays connected in the differential circuit, and these should be set to operate in not less than one-quarter second under short-circuit conditions.

Auxiliary relays in combination with reverse power relays are provided for a number of purposes: For time characteristics when required in the relay equipment for the protection of parallel lines where a time delay is desired and cannot be taken advantage of in the overload relays, i.e., instantaneous operation for either line with both lines in service and time delay for the operation of the single remaining line. For instantaneous operation to disconnect the alternating-current potential circuits of the reverse power relay until after the instantaneous overload relays have operated, thereby insuring that the reverse power relay contacts will be normally in the neutral position, and, therefore unprejudiced in the event of a fault. For locking purposes, to prevent the second of a pair of lines from being tripped for a definite time after the first has been opened, thus preventing faulty operation of the equipment due to energy surges on the system which may prevail after the faulty line has been properly cleared. Such energy surges are made possible by dropping the voltage at short circuit to such a value that synchronous apparatus may fall out of step.

Reverse power relays are made for either D.C. or A.C. tripping. Similarly, a distinction must be made between uni-directional relays, which operate to cause the tripping circuit to be closed when the power is in one direction, and duo-directional relays, with which, when the power is in one direction in the relay, one set of contacts are closed for controlling one circuit, and, when the power is reversed in the relay, another set of contacts are closed for controlling another circuit. Normally, both sets of contacts should be in the open position.

As previously mentioned, induction-type reverse power relays are very sensitive and reliable. Certain types will thus operate and function successfully on single-phase short circuits, even where the voltage between the two phases that are short-circuited may fall to zero. With balanced three-phase short circuits, they will function with 10 amperes or higher secondary current and 1 per cent of normal voltage Relays intended for protection against feed back in single lines will operate where the reversal of power at normal voltage is as low as 3 per cent of normal current.

Care should be taken in applying reverse power relays to single lines for protection against line faults which have their neutrals grounded through a high resistance. Under some conditions of grounded lines there may not be a net reversal of power, and the operation of the relay

may not be insured. These relays should not be applied where the current in the neutral is limited to less than twice normal current. Also, in cases where alternating current is used for the tripping circuit, supplied by tripping reactors, it is very necessary that sufficient current flow through the neutral to supply energy for the tripping circuit.

In selecting the proper type of reverse-power relay, consideration must also be given to the phase relation between the voltage and the current in the circuit at the time when the relay is to operate. This relation of current and voltage may vary greatly in different cases. Thus, when used for protection against line faults, the relay equipment almost invariably encounters a condition of lagging current; while when used for protection against the "running light" of alternators as synchronous motors, it will be required to operate under conditions of a leading power factor. In the case of protection of lines against feed back, under otherwise normal conditions, the relay equipment may be required to operate under the more usual conditions of a lagging power factor, or in some cases under the condition of a leading power factor.

A different connection of the driving elements is therefore necessary to give satisfactory operation under these conditions. The elements of relays which are to be used for protection under conditions of lagging power factors are thus connected in the circuit, so that at unity power factor the voltage across the potential coil and the current in the current coil are in quadrature. The relays which are to be used under a condition of leading power factor have an adjacent or 30° connection.

Of the numerous applications of directional relays, only the most common will be described. They are as follows:

1. Reverse-power protection of single incoming lines.

2. Balanced protection of two parallel incoming, outgoing, or tie lines.

3. Balanced protection of three or more parallel incoming, outgoing, or tie lines.

It will be impossible, on account of limitation of space, to give connection diagrams for all possible conditions under each case, such as for grounded or non-grounded systems, A.C. or D.C. trip, etc. This may, in many cases, considerably affect the arrangement, and the connections and the diagrams shown are intended only as a guide in explaining the different applications. Very complete diagrams and instructions can readily be obtained from the relay manufacturers.

With *reverse power protection* of *single incoming lines*, a distinction is generally made between protection against line faults and protection

against a reversal of normal power under otherwise normal conditions.

Figure 352 shows connections for such a scheme with a non-grounded system and with D.C. trip. The tripping circuit is completed through the contacts of the overload and reverse power relays, the overload relay preventing the opening of the line on small reversals and also permitting the use of time delay where required. With A.C. trip with tripping reactors, and where instruments and meters are to be taken

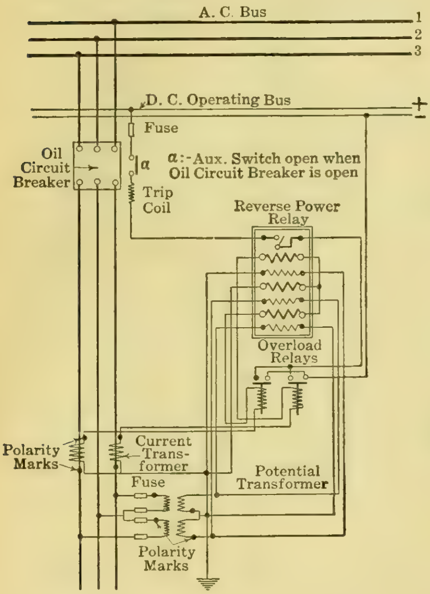


FIG. 352.—Reverse Power Protection for Single Lines Where Direct Current is Available for the Tripping Circuit. (Neutral not Grounded.)

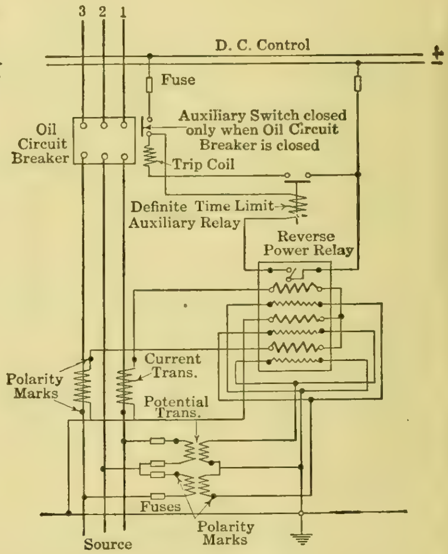


FIG. 353.—Protection against Reversal of Power in Single, Three-phase Lines Under Otherwise Normal Conditions. (Neutral not Grounded.)

care of in addition to the relay load, two sets of current transformers are required. It is then recommended, where possible, to connect the relay and instruments to the same set of current transformers and not to the transformers supplying the tripping reactors.

Where it is desired to open a circuit upon the reversal of normal power, i.e., in cases where two systems are interconnected, one receiving power from the other, but it is desired to prevent any great amount of power from flowing in the opposite direction, such a scheme as that shown in Fig. 353 can be used, the reverse power relay is connected

directly to control a definite time-limit relay and is not connected through the contacts of overload relays, as is the usual case when protecting against line faults. This arrangement permits the reverse power relay to begin to operate the definite time delay auxiliary relay at very low reversals of power. The contacts of the reverse power relay open when conditions again become normal. Any energy surges on the line will not cause faulty operation, as the definite time relay is set for a time delay sufficient to take care of these conditions.

The manner in which *balanced* protection is applied to *two parallel lines*, with power flowing in either direction by means of differentially connected over-current relays, has already been explained. The protection thus afforded, however, does not discriminate between the two lines, which are both disconnected on a fault in either.

In order to obtain a discriminating action, reverse power relays may be included in the scheme (Fig. 346), in which case the connections would be as shown in Fig. 354. As in the indiscriminating case, so long as a balanced condition is maintained between the corresponding phases in the two lines, there will be no current in the differential or relay circuit. When a fault occurs, an unbalanced condition of the currents will result, and the vectorial difference will flow through the current coil of the relays. This will cause rotation of the disc in a direction indicative of the faulty line, and will close the corresponding contacts of the directional relay. Overload relays are used, as already explained, to prevent tripping of the breaker on small values of unbalancing, or on unbalancing of a transitory nature. In the diagram, the arrows may be considered as indicating the direction of power flow,

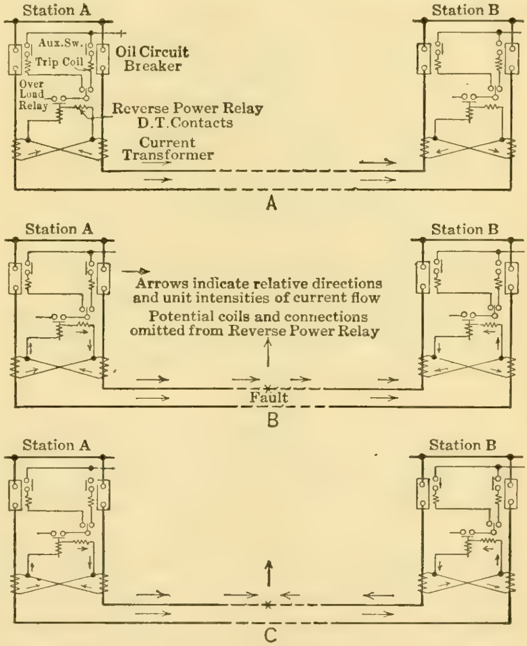


FIG. 354.—Balanced Power Protection for Two Parallel Tie Lines. (Discriminating.)

and the moving contact of the reverse power relay will travel in the direction of the arrow indicated below the relay coil.

Many different combinations are possible with the balanced system of protection. Instantaneous action may be had on reversal in one line with both lines in service, and the opening of the breaker in the faulty line will then automatically introduce overload and time delay in the good line.

In general, it is considered preferable to introduce a short time delay even with the two lines in service, and Fig. 355 shows such an arrangement for a grounded system. Two sets of overload relays are connected in series with the reverse power relay across the differentially connected current transformer secondaries. The set of overload relays with the lower time settings operate first in case of a fault in either line with both lines in service.

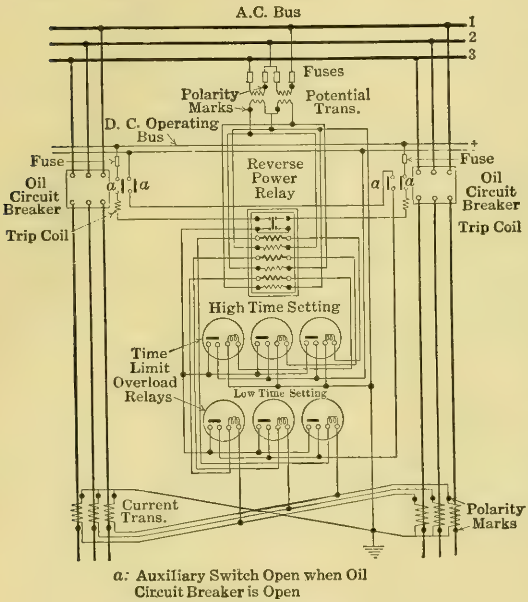


FIG. 355.—Time-limit Balanced Power Protection for Two Parallel Incoming, Outgoing or Tie Lines with Time Delay for Single Line Operation (for grounded Neutral or Four-wire Systems).

The tripping circuit for the overload relays with the low settings is connected through auxiliary switches on both breakers, so that after one breaker has opened the tripping circuit of the remaining breaker must be completed through the contacts of the overload relays with the longer time setting. This arrangement gives the desired longer time delay with one line in service.

It is also possible by means of one set of overload relays, Fig. 356, to introduce the same time delay with both lines in service as for single line operation. In order to prevent the second line from tripping, due to energy surges on the system, which may prevail after the faulty line has been properly cleared, it is advisable to provide auxiliary locking relays. These consist of an instantaneous opening and a time-delay

reclosing relay. The tripping current for the circuit breakers is carried through the coils and contacts of these relays in such a way that when one breaker is being automatically tripped, the relay trip circuit of the other breaker is opened by the locking relays, which have been set to remain open long enough to permit conditions on the system to become normal. After this has occurred, the second line can be tripped in case of an overload which remains on a sufficient time, provided the power flow is from the bus to the line. This scheme of locking relays is very widely used and recommended, even for the arrangement shown in Fig. 355.

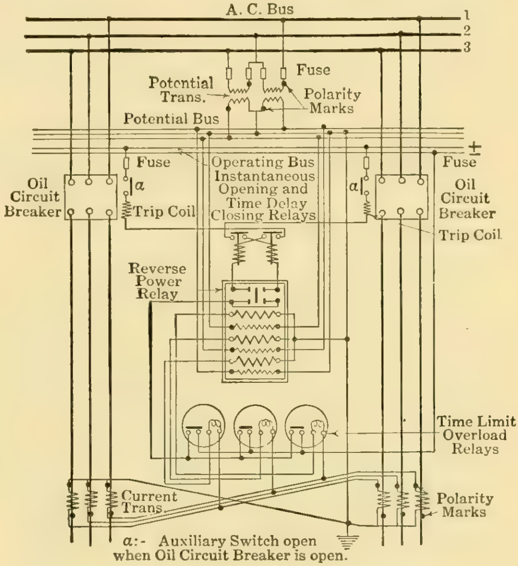


Fig. 356.—Time-limit Balanced Power Protection for Two Parallel Incoming, Outgoing or Tie Lines with grounded Neutrals.

Since the balanced schemes, as described, are not affected by through short circuits, it is obvious that if protection is desired against short circuits on the buses, for example, separate overload relays are required. These can be connected to the same current transformer secondaries as the other relays and would necessarily have to be set for higher time values than the over-current relays used in connection with the directional relays. In case of through short circuits they would trip both breakers.

For *three or more parallel lines*, where discrimination between the last two remaining lines is not important, the *balanced over-current* scheme previously described and illustrated in Fig. 348 may be used. In the case of important balanced parallel lines, where discrimination even between the last two remaining lines is essential, reverse power relays in connection with overload relays should be used, a typical diagram of such a scheme being shown in Fig. 357.

The current transformer secondaries are all connected in series in a loop circuit, so that when the primary currents are all equal the secondary currents will also be equal and will circulate through the loop

as one current, and practically none will pass through the coils of the overload and reverse power relays which are connected across each current transformer secondary. Inasmuch as the success of the scheme depends upon the relatively low impedance of the loop circuit as compared to the impedance of the coils, it will be apparent that some method is necessary to eliminate the useless impedance injected in the loop circuit by the relays of a dead feeder. This is accomplished automatically by short-circuiting the relay equipment of the line whose circuit breaker is open, by means of auxiliary switches on the circuit breakers or by auxiliary relays controlled by such auxiliary switches.

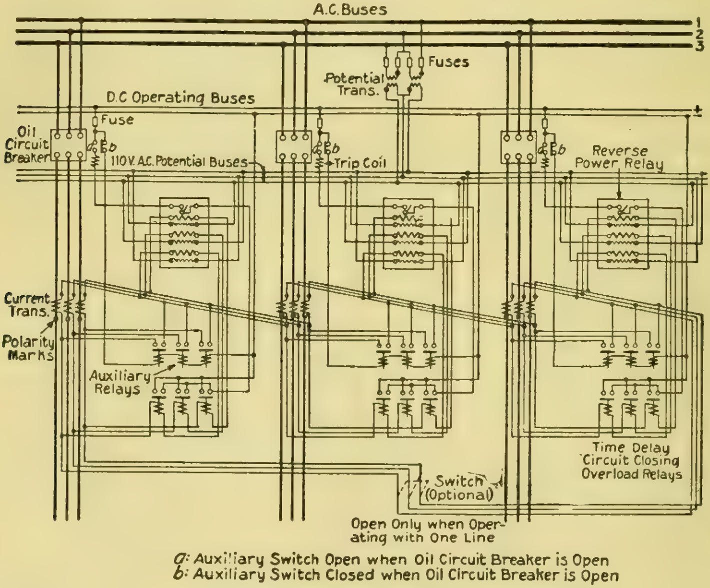


FIG. 357.—Balanced Power Protection for Three or More Parallel Incoming, Outgoing or Tie Lines.

It will be noted that when all but one line is out of service, the relay equipment of this line will be short-circuited by the auxiliary switches or relays referred to in the preceding paragraph, and accordingly the last line will be non-automatic unless some means is provided to open the loop circuit. This opening of the loop may be accomplished manually, or it may be done automatically with considerable complication of auxiliary switches, etc., which complication is usually considered inadvisable. When the loop has been opened, each feeder will be left with overload and reverse power protection, at values determined by the settings of the overload relays.

If an open circuit should occur in one of the conductors, or if, when putting another line into service, only the breaker at one end is closed, an unbalanced condition will result which may tend to open the good lines in use, if the current flowing at the time is sufficiently great. This danger becomes relatively smaller as the number of lines involved is increased, because the secondary unbalancing will be inversely proportional to the number of lines in service. For instance, if the overload relays are set to operate at the normal load of each feeder, and if four lines are in, three continuous and one broken, an overload of four times normal on each feeder would be required before any trouble would be encountered. The break would usually be detected before this excessive current occurred.

Alternators can also be protected with reverse power relays against internal troubles caused by shorts between the windings and grounds, where the neutral is grounded. Such protection should only be used where it is not possible to bring out both ends of each phase of the generator winding, in which case differential protection is usually recommended and preferable. Figure 358 shows a wiring diagram for reverse power protection of a generator with the neutral grounded. Where the neutral is not grounded, two current transformers and two overload relays only are required in addition to the reverse power and auxiliary relay.

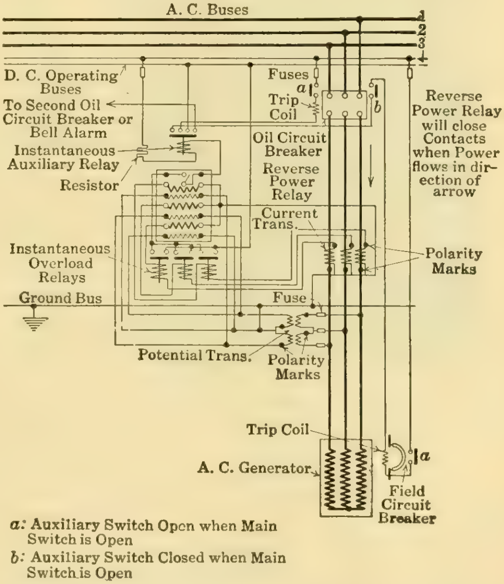


FIG. 358.—Reverse Power Protection for Alternators where Both Ends of the Alternator Windings are not Brought Out and the Neutral of the Generator Circuit is Grounded.

Provision for automatically opening the alternator field circuit, after the oil circuit breaker has tripped, should also be made, as previously explained in connection with the protection of alternators, by differential connected over-current relays.

Differential Relays. Differential protection may be accomplished

by the use of differential relays or by relays differentially connected, as already described. Differential relays depend for their operation upon the resultant force due to relation of the currents in two or more circuits within the relay itself.

Most differential relays are of the mechanically balanced circuit-closing type with instantaneous action, and are mostly used for the protection of parallel transmission lines in case of unbalanced currents in similar phases, such as would be occasioned by a fault in one of the lines. They operate on current alone, tripping the line carrying the greater current. For this reason, they may not be used for incoming lines unless there is some source of power at this end, to insure that the injured line will carry the greater current.

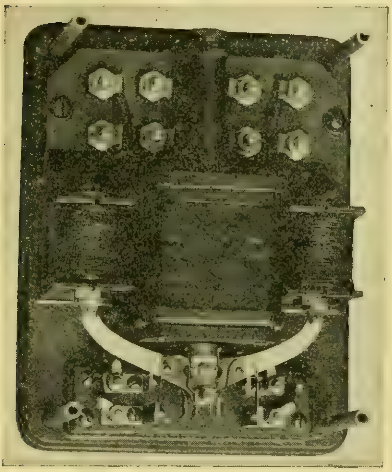


Fig. 359.—Instantaneous Mechanically Balanced Differential Relay.

Figure 359 shows a very satisfactory mechanically balanced differential relay and Fig. 360 a diagram of one method of connection. In this particular case, two sets of overload relays are provided, insuring instantaneous balanced protection and at the same time an overload time-delay protection for through shorts. When a fault occurs in one line, and this is cleared by the opening of its breaker, the same overload time-delay will be automatically introduced for the remaining good line.

The relay is made in single pole units only, each consisting of three solenoids which control a moving contact mechanism. The two smaller outside solenoids, connected in series with the current transformer secondaries, tend to hold the moving mechanism down, while a differential current passing through the larger center solenoid will tend to raise the mechanism upward. When the difference becomes sufficiently great to overcome the weaker of the two small solenoids, the contact mechanism will be operated on the side to trip the breaker carrying the heavier current. So long as a balanced condition exists and there is no appreciable difference in the reactance of the two lines, the relay will not trip either breaker if the differential current is less than that required to unbalance the relay, no matter how high the current may be in the two lines. For a successful operation of the relay

it is generally required that the faulty line should carry at least 50 per cent more current than the good line.

In case of light short circuits or high resistance grounds, where the unbalance in currents may be too small to operate the mechanically balanced differential relay just described, an *induction type differential relay* is available. It is also recommended in cases where bushing

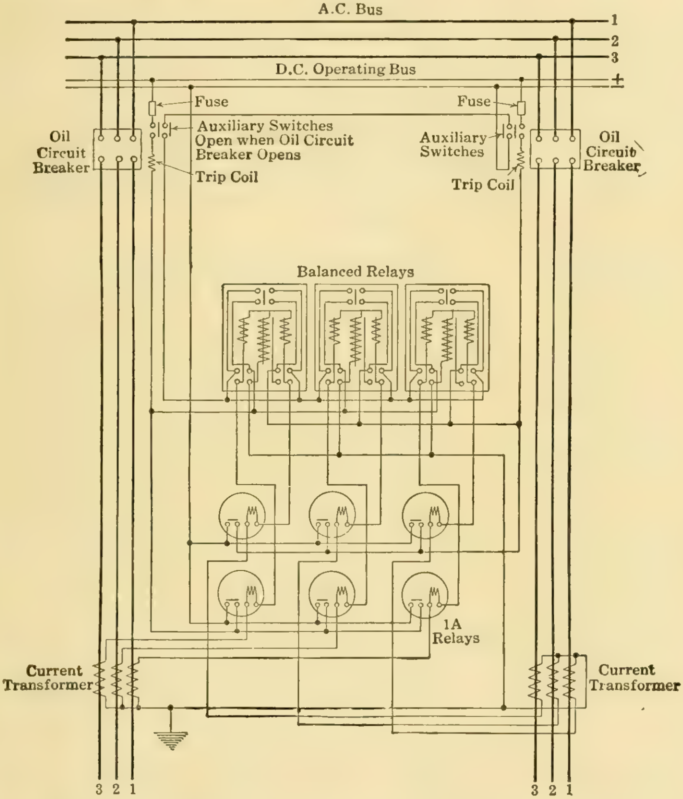


FIG. 360.—Connections for Mechanically Balanced Differential Relays in Connection with Over-current Relays.

transformers are used and where, owing to a low primary current and high current transformer ratio, the secondary currents may be very small. It is constructed on the principle of the induction overload relay. Each element contains a disc acted upon by two U-shaped electromagnets with a main coil and pole shading coils. One of these tends to rotate the disc to close the contacts, while the other tends to rotate it in the opposite direction and holds it against a stop on a small lever.

In the majority of cases, practically instantaneous operation is desired; therefore, the time lever, which controls the position of the stop, is usually set at the lowest lever setting point. If a time delay were desired, it would only be necessary to move the lever to a higher setting position, thereby increasing the angular rotation of the disc before closing the contacts.

This type of relay therefore operates on current alone, and is also, strictly speaking, of a mechanically balanced type. Like the previous type of relay it should only be used where it is certain that the current in the faulty line is greater than in the good line, as at the generating station end of the lines. It should be used at the sub-station end only if a source of power is available at this point. The relay may also be used for differential protection of alternators and transformers and also for pilot wire protective schemes.

Ground Relays. In solidly grounded systems, ground protection is generally taken care of by the ordinary phase relays; but with non-grounded systems or systems grounded through a comparatively high resistance, these relays, set for short-circuit protection, may not be able to operate in case of ground faults. The general practice in such instances is, therefore, to connect a residual or ground relay in the neutral lead of the current transformer secondaries. Under normal conditions or balanced overloads, no current flows through the neutral lead of these current transformers, but as soon as a ground occurs the unbalanced residual current flows through this connection, operating the ground relay, which in turn opens the circuit breaker.

These residual ground relays can therefore be set at a much lower value than the phase relays, and they may also be given time and current gradings in the same manner as these. The general practice is to use phase relays in each of the three phases and the residual relay in the neutral. They are, however, operated from the same current transformers, although the operation is entirely independent. Either overload or reverse power relays, or a combination of the two, may be used for ground protection, depending on the conditions under which they are to operate. The reverse power relay is more sensitive to small currents in the neutral wire than is the current relay, because of the potential connection. The reverse power relay is, of course, also required in cases where control of the direction of the ground current is involved.

Ground relays are also desirable in connection with balanced protective schemes using directional or differential relays where the system is grounded through a comparatively high resistance, limiting the ground current to less than twice normal full-load current. In such a case, the three-element reverse power or differential relay would fail to

operate on a ground, the reason naturally being that two of the elements would be operating in normal direction to hold the contacts open, while the third element, actuated by the ground current, would pull in the other direction to close the coils, and, unless the torque due to the ground current was greater than that due to the other two, the relay could not close. When ground relays are thus used in connection with balanced directional relays combined with overload relays, the contacts of the ground relays are connected in parallel with the contacts of the overload phase relays, thus leaving the reverse power element to discriminate as to the direction of the flow.

For protection against through ground faults with balanced differential schemes, such as a ground on the incoming line buses, ground relays can be connected to the differentially connected current transformers in the incoming lines through 5 : 5 ampere auxiliary current transformers which will thus sum up the total ground current and trip the two parallel lines.

Split-conductor Relays. This system consists in splitting each conductor into two parts and using a relay which operates whenever the current in the two halves becomes unbalanced. The diagram (Fig. 361), illustrates the connections for one conductor. It involves a standard overload relay but a special current transformer. This has three windings; two primary, to which the two halves of the split conductor are connected, and one secondary, connected to the relay which controls the circuit breaker trip coil. Under normal operation the current divides equally between the two parallel paths and in each transformer the magnetizing effect of the two primary coils are equal and opposite. The transformer, therefore, offers no impedance to the current flow, and the secondary windings and relays are unaffected. If a fault develops in one of the two parallel conductors, however, it is evident that the balance between the two primary transformer windings will be upset, thus producing a magnetizing effect on the secondary windings, exciting the relays and tripping the circuit breakers.

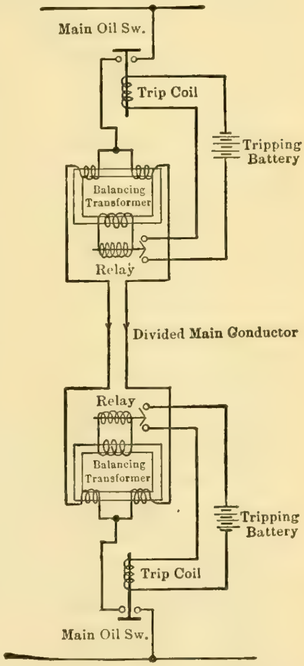


Fig. 361. — Split-conductor Method of Relay Protection.

Pilot Wire Relays. For a single line, over which power may normally be fed in either direction, balanced relays at each end of the circuit, connected by means of pilot wires, will open both ends of the line whenever trouble exists therein, but not otherwise. This device is particularly adapted to loop or ring systems; and the connection of two stations by pilot wires thus has the effect of making these two stations

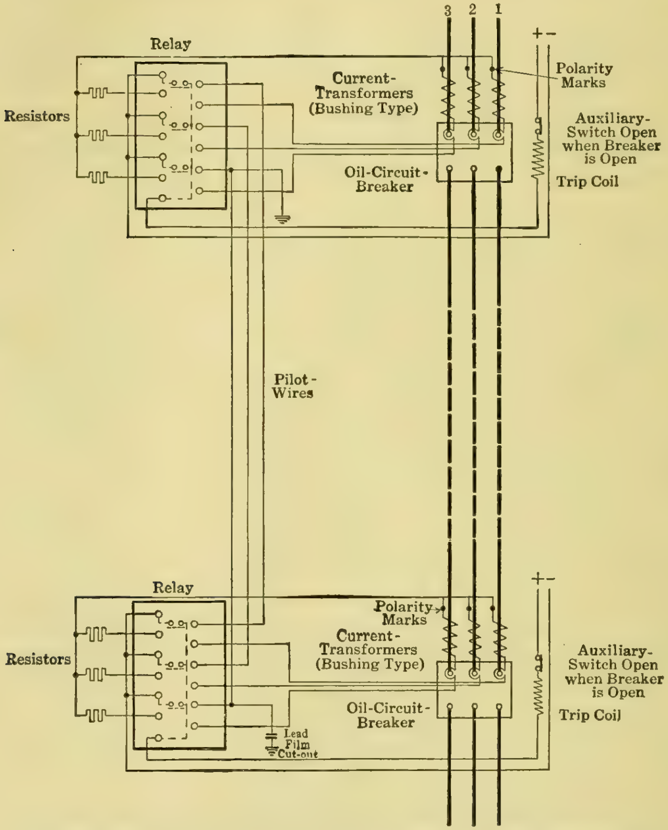


Fig. 362.—Pilot Wire Protective Scheme Using Differential Relays.

a unit in the loop, thereby reducing the necessary number of time spacings by one. When only one or two sections in a loop are to be provided with pilot wire protection, and the remainder is provided with time-delay relays, it is best practice to place the pilot wire section near the center of the loop.

Figure 362 shows a typical scheme of pilot wire protection. Each line to be protected requires three pilot wires between the two stations

and two triple-pole differential induction relays. There are two parallel circuits across the secondary of each current transformer. One of these consists of the restraining coil of one element of the relay in series with a resistor; the other contains an operating coil of one relay, one pilot wire, an operating and restraining coil of the other relay and two parallel circuits back to the current transformer, each passing through the restraining and operating coils of another element in both relays and a pilot wire. When the line current at both stations is equal, equal currents flow through the first circuit, consisting of the restraining coil and resistor at each station and the potential at both ends of each pilot wire is the same. Consequently no current flows through the operating coil, regardless of the magnitude of the line current. If, however, the currents at each station are not equal in magnitude or phase relation, different potentials are impressed on the ends of the pilot wire and a current flows which is proportional to the difference in potential. The current flowing through the operating coils of one element of each relay causes them to close their contacts and trip the breakers at both ends of the line.

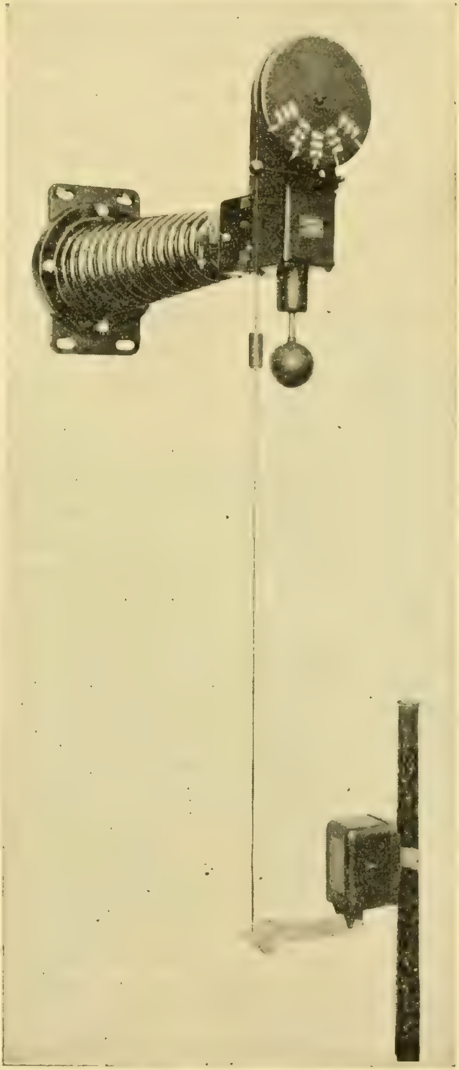


Fig. 363.—Series High-voltage Overload Time Limit Relay.

High-voltage Overload Relays. Series overload high-voltage relays may occasionally be desirable, as in cases where bushing transformers

would not permit a sufficiently low overload setting. Figure 363 illustrates such a relay. It consists of two separate elements joined by an impregnated paper cord. The current coil, and calibrating device are mounted on a post insulator, well out of reach, and the contact parts with time element and enclosing cover are so mounted as to be easily accessible for adjustment.

The current element consists of a solenoid coil, the plunger of which is connected to a sprocket on the shaft of a calibrating wheel which is marked in line amperes. A cord passing over a groove in the calibrating wheel and carrying a small weight, with a spring to absorb shocks on the cord, is connected to the operating arm of the lower or contact element, which may be provided with a time-delay device if desired.

Over-voltage Relays. These may be either instantaneous or time limit and are similar in construction to overload plunger-type relays, differing only in that potential windings are substituted for the current coils. They may be used to protect generators, transformers or other power apparatus against damage due to abnormal voltages. For this purpose the relay should be connected so as either to open up the field circuit of the alternators or introduce into each field circuit a sufficient resistance to insure a reasonably low potential on the system.

The condition most frequently responsible for a dangerous rise in potential is the loss of load on a power-station while the generators are operating under considerable excitation. The abnormal voltage is, therefore, usually accomplished by a decreased current. To guard against the possibility of opening the field circuit under any condition, other than the loss of load, a circuit-opening overload relay or circuit-closing underload relay may be connected to the line with its contacts in series with those of the over-voltage relay.

Low-voltaje Relays. These are generally of the plunger type and may be either circuit opening or circuit closing or both; that is, the relay may be provided with two sets of contacts, each controlling one circuit. Under normal voltage conditions, in the latter case, with the plunger raised the upper contacts are closed. When the voltage drops to a predetermined value, the plunger falls, opening the upper contacts and closing the lower set.

Low-voltage relays may be either instantaneous or provided for time-delay, this being either accomplished by means of air bellows or oil dashpots, the latter generally being used where a very long time delay is desired.

Under-current Relays. These are made with circuit-closing contacts for instantaneous operation and are similar to low-voltage relays,

with the difference that current coils are substituted instead of potential coils.

Trip-free Relay. This is a safety device intended for use with electrically controlled circuit breakers; its purpose is to prevent them from being held closed on overloads. To accomplish this, the trip-free relay is simply added to the standard control wiring. When the overload relays operate, the trip-free relay is operated at the same time the breaker is tripped. The operation of the trip-free relay opens the closing circuit of the breaker and establishes a circuit from the closing contacts of the control switch, through a holding coil on the trip-free relay. If a breaker opens on overload while the control switch is in the closing position, the breaker will not close again so long as the control switch is held in the closing position.

Control Relays. These are used in connection with the control switches for electrically operated oil circuit breakers, etc. Since these control switches, as a rule, are not constructed to open a current of sufficient capacity to operate the closing coil of the solenoid, for example, it is necessary to use a control relay with its operating coil connected across the closing contacts of the control switch and the relay contacts in series with the solenoid closing coil.

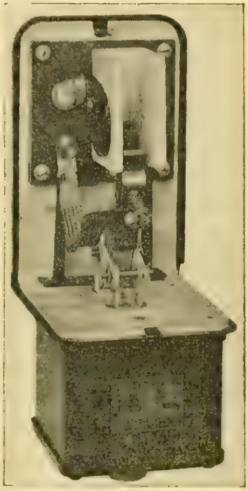


Fig. 364.—Instantaneous Control Relay (Cover Removed).

Control relays are generally of the instantaneous-acting, circuit-closing plunger type. Figure 364 shows such a relay, the contacts being closed through a toggle mechanism when the coil is energized and the plunger raised. The contacts are here provided with blow-out coils to avoid unnecessary burning at their tips.

When a solenoid-operated circuit breaker is automatically closed, it is desirable that the closing circuit be opened when the breaker closes, this being accomplished by means of an auxiliary switch on the breaker. Unless such an auxiliary switch opens at the final moment of the act of closing, there may be danger of the breaker failing to latch. For such conditions a so-called *hesitating* control relay may be used, in which the contacts open with a certain delay after the control magnet circuit is open. The required delay is caused by a short-circuiting collar on the core of the operating solenoid. A further delay is caused by arranging the mechanism so that the

plunger has to fall a certain distance before operating the contact device.

Auxiliary Relays. These may be used to automatically close or open direct or alternating current control circuits within certain limits of capacity. There are many different types, one particular construction being of the well-known magnetic-contactor type with certain modifications.

An auxiliary relay may thus be used in connection with an overload relay, to relieve the latter of making or breaking a comparatively large current on its contacts. It may be used to seal in a circuit made by another relay, so that once current is thrown on the tripping coil of the oil circuit breaker, the current will remain on until the breaker opens and the tripping circuit is opened by an auxiliary switch on the oil circuit breaker. It may also be used in one circuit to control a second circuit which is to be operated simultaneously, and for various other combinations.

Signal Relays. These are used for indicating to the attendant the automatic opening of circuit breakers. When these are closed by hand and opened either by hand or by some automatic tripping arrangement, a circuit-closing auxiliary switch for closing the alarm circuit is so mounted on the operating mechanism that when the circuit breaker is opened by the hand-closing mechanism, the auxiliary switch does not operate. But if the tripping is effected by the automatic mechanism, the auxiliary switch will close and throw in circuit the alarm device.

On electrically operated circuit breakers no arrangement of a mechanically operated auxiliary switch, which will allow it to distinguish between the non-automatic and automatic opening, can be conveniently made. Consequently, the means employed to inform the operator of automatic opening is generally a bell-alarm relay with its operating coil connected in the power supply of the circuit-breaker tripping coils. The operation of the relay is not affected by the control switch circuits, and is energized only when current passes through the tripping circuit contacts of one or more of the protective relays.

Whenever a circuit breaker is automatically tripped, the relay coil is energized for an instant through the circuit of the overload trip. As it may be necessary to ring an alarm bell for some time to attract the operator's attention to the fact that a device has been opened automatically, the relay plunger is notched so that it remains up in the closed position until pulled down by hand, which shuts off the alarm bell by opening the bell-alarm circuit.

Automatic Reclosing Equipment. Such equipment accomplishes exactly what an operator would do; that is, it recloses a breaker which has been opened by the operation of an overload relay. Such equipment has been standardized and includes overload relays which cause the oil circuit breaker to open and disconnect the load in case of an overload or short circuit.

A combination of reclosing and notching relays allows the circuit breaker to be closed twice before the circuit is finally locked open by the action of the notching relay. This relay is designed to open its contacts after the coil has been energized three times, provided the time interval between each impulse is less than a predetermined period. If the overload or short circuit disappears and does not recur within the predetermined period, the circuit breaker remains closed on the first or second step of the notching relay and interruption of line service is avoided. In this event the notching relay returns to its first position and a subsequent overload will start a fresh sequence of operation.

In detail the sequence of operation is as follows:

1. An overload occurs on the line.
2. The overload relay trips the circuit breaker.
3. The circuit-closing auxiliary switch on the circuit breaker is closed.
4. The notching relay makes one step instantly.
5. The reclosing relay operates in a definite time, permitting the control relay to be energized and cause the closing of the circuit breaker.
6. The circuit-closing auxiliary switch on the circuit breaker is opened.
7. The reclosing and control relays then open.
8. The notching relay starts to reset and will do so if the circuit breaker does not open again in a predetermined time. If it should reset, the first step made as described above will be lost, and all further action will take place as if the breaker had not opened at all.

If the circuit breaker opens within this predetermined time before the notching relay resets, the complete cycle will repeat itself, except that the notching relay in this case will make the second step. If the circuit breaker opens the third time before the notching relay is reset, the latter will make the third and final step and will prevent the breaker from reclosing until the relay is manually reset by the operator.

Switchboards. The switchboard of the modern large power station is, strictly speaking, not a switchboard in the original sense of the word. While for small stations the entire instrument and switch equipment may be mounted directly on the board, for large stations the oil circuit breakers and busbars are always mounted at some distance from the board, the location being determined by conveni-

ence of wiring, and safety. In such a case the switchboard is rather a control board and contains only the control switches, and instruments, and the various other auxiliary devices, such as indicating lamps, plugs and receptacles for measuring the voltage and for synchronizing, etc.

The design of a switchboard involves a careful consideration of the apparatus to be controlled, the system of connections, arrangement of cables and other wiring, and the general design of the station. The various apparatus on the board should be arranged so as to facilitate the operation, and for this reason the board is always divided into panels corresponding to the machinery or circuits which are to be controlled. The exciter and the regulator panels are generally located at one end, then the generator panels, station panel, transformer and outgoing line panels, in the order mentioned. This arrangement may, of course, be varied in order to correspond more closely to the arrangement of the apparatus. Blank panels should preferably be provided at the beginning, for future machinery. The expense of such panels is very little and it considerably facilitates the addition of instrument equipment for future units. In such a case it will only be necessary to remove the blank panels, have the necessary instruments and wiring mounted thereon, then replace them on the framework and make the necessary remaining connections, thus causing the least disturbance to the rest of the equipment.

Pipe framework is now almost universally used for supporting the panels, on account of its neatness and simplicity. By means of standardized fittings, the panels can readily be fastened to the uprights, and it is then easy to attach to the uprights or tie-rods accessories mounted on the back of the panels, such as buses, fuse bases, current and potential transformers, etc.

The material for the panels may be slate or marble. Slate, which is suitable for switchboard work, must be carefully selected for insulating qualities as well as strength, and when used in its natural color must be selected for appearance as well. The three varieties used are natural black slate, dull black marine-finished slate and black enamel slate. Natural black slate is now considered the standard material.

There are several varieties of marble suitable for switchboard work, the most serviceable being blue Vermont marble. Pink and gray Tennessee and white Italian marble (domestic) are used to some extent. Panels of marble are always polished on the front and exposed edges, and varnished on the back. A dull black or black enamel finish can be applied to marble, if desired. However, the process of black-enameling the marble makes it brittle, rendering it an undesirable material for switchboard use.

Owing to its greater strength, slate is recommended for all switchboard work when the potential used directly on the panel does not exceed 1200 volts for natural black slate and 650 volts for dull black marine-finished slate. Marble is suitable where the potential used directly on the panel does not exceed 3500 volts, and must be used in all cases where the potential of apparatus mounted directly on panel, without the use of insulating bushings, exceeds 1200 volts.

Natural black slate is best suited for switchboard work, as it is not

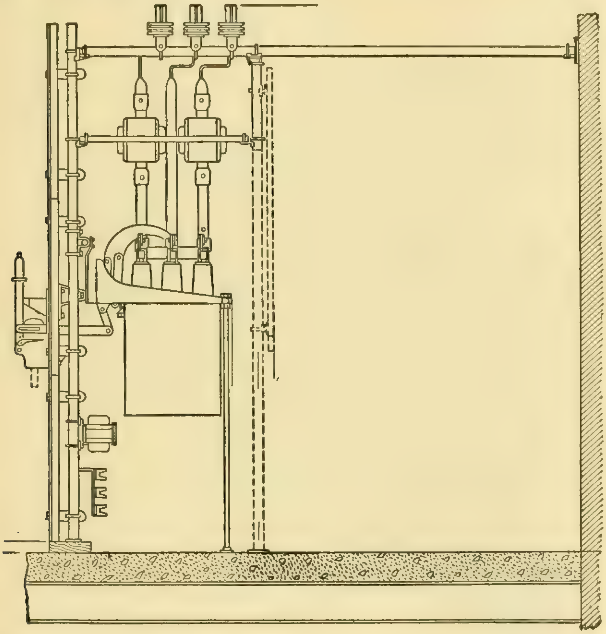


Fig. 365.—Arrangement of 2300-volt Switchboard with Circuit Breakers Mounted on the Pipe Work Supporting the Panels.

easily marred or stained, and can readily be matched when extensions are to be made.

The small wiring on the back of the panels should be done neatly and regularly, to facilitate tracing of connections, and it should be arranged in a manner best suited for connection to the control wires coming to the board.

The back and ends of the board may be closed by a wire and grillework screen, to prevent tampering with the apparatus back of the panels. Such a screen will also improve the appearance of the installation and help to protect the operator and others against accidental contacts with live parts back of the board.

Switchboards may be classified according to the style of construction or according to the manner in which the oil circuit breakers are mounted and controlled. Based on design we have:

1. Vertical panel boards.
2. Bench boards.
3. Safety enclosed boards.

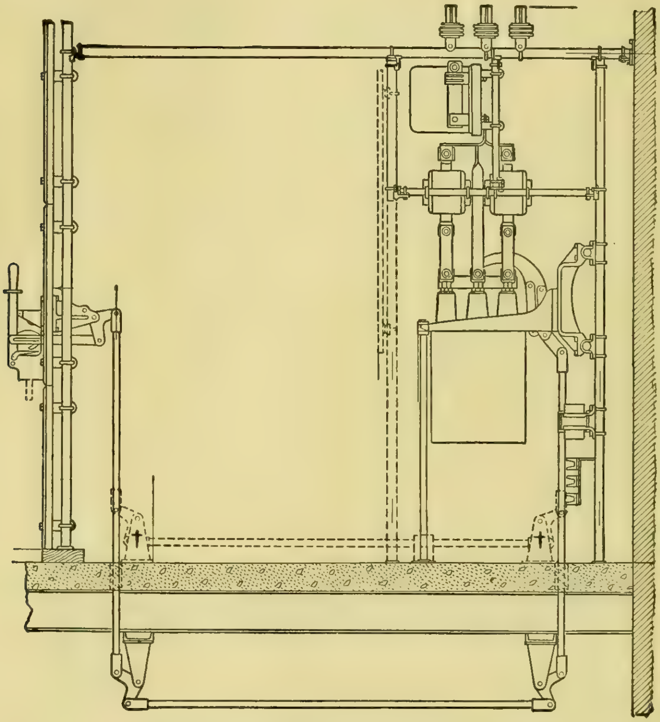


FIG. 366.—Arrangement of 2300-volt Switchboard with Mechanically Remote-control Circuit Breakers Mounted on Open Pipe Work.

And, according to method of control:

1. Direct-control boards.
2. Manual remote-control boards.
3. Electrical remote-control boards.

The self-contained switchboard is always of the vertical type, Fig. 365, and has all the apparatus, including the oil circuit breakers, mounted near the panels.

The mechanical remote-control board is also of the vertical panel type, Fig. 366, but the oil circuit breakers and busbars are mounted

on a pipe or other structure somewhat to the rear of the panels, the breakers being operated by handles, located on the front of the panels, through the medium of mechanical connecting pipes.

The electrical remote-control switchboard may be either of the vertical panel type or of the bench-board type, depending on the conditions to be met. The oil circuit breakers and the busbars are installed in the most convenient place in the station, often at a considerable distance from the board. The breakers are then operated by means of

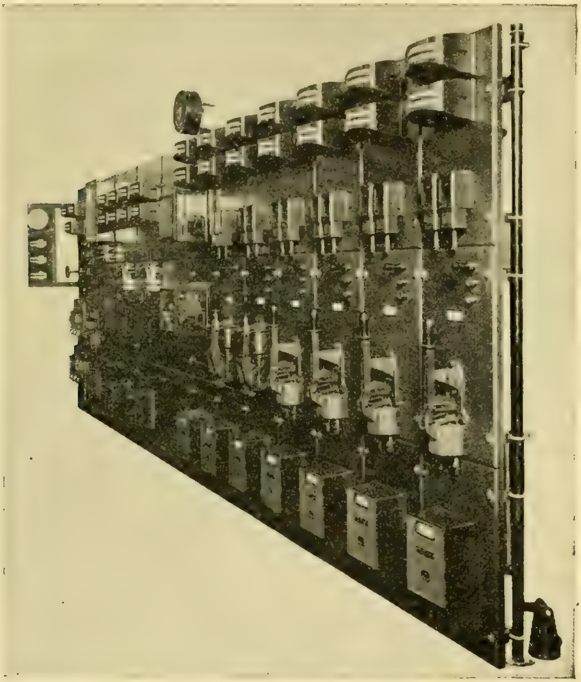


Fig. 367.—Typical Vertical Type Switchboard with Manually-operated Oil-circuit Breakers, Front View.

solenoids or motors, which in turn are controlled from the switchboard.

The proper type of switchboard to be selected depends on the apparatus involved, particularly the oil circuit breakers and the busbars, and these in turn on the power to be handled, the voltage, operating features, space available, etc.

With stations of large capacity and high transmission potentials, requiring a heavy switching equipment, manual control is practically impossible, partly from mechanical reasons and partly on account of

the increased space factor required by the breakers, buses, etc., and recourse is had to the methods of remote control.

Commencing with the manually operated remote-controlled switches equipped with rods and bell cranks, good practice finally recognized the desirability of employing solenoid or motor-operated breakers controlled from a central point. This arrangement permitted the location of the control board without reference to the location of the breakers or the apparatus which they control. Absolute isolation

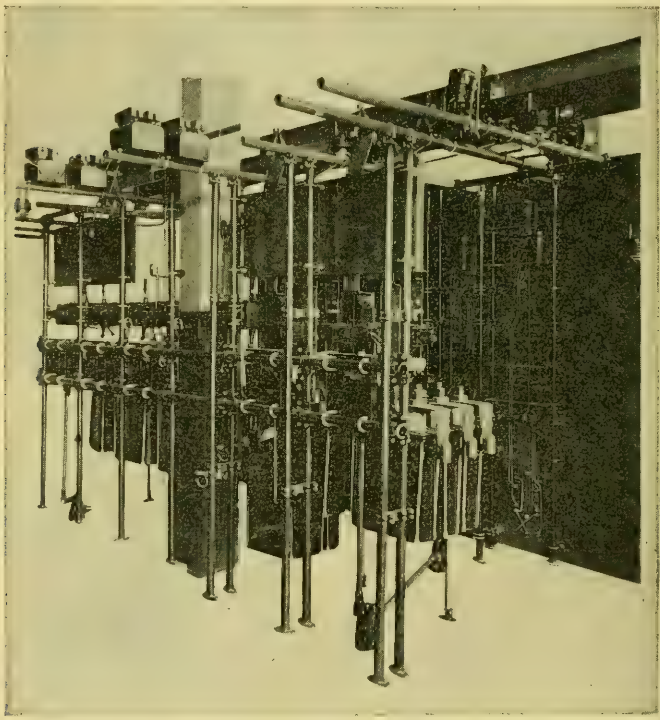


FIG. 368.—Rear View of Switchboard Shown in Fig. 367.

of the high-tension equipment may thus be secured, thereby largely eliminating the personal hazard and danger of accidental contact and making possible the use of the minimum amount of high-tension buses inside the station.

It is difficult to give any accurate recommendation as to where the dividing line between the different arrangements should be drawn. In general, however, it may be said that those shown in Figs. 365 and 366 can be used for voltages up to 6600 and station capacities not

exceeding 5000 kilowatts. For higher capacities and voltages it is advisable to mount the oil circuit breakers in compartments. In fact, most high capacity switches for moderate voltages are made for cell mounting, but above 15,000 volts they are, as a rule, of the open design.

Figures 367 and 368 show the front and rear views of a typical

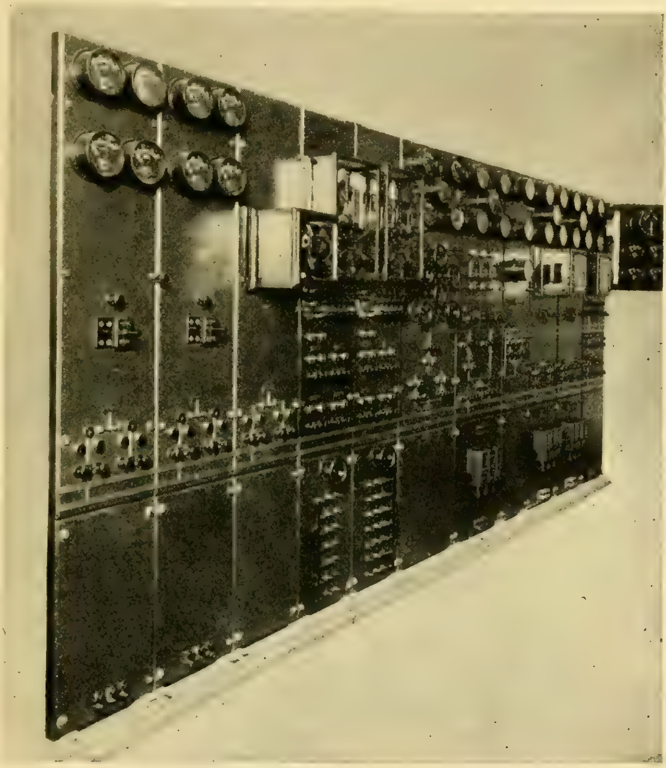


FIG. 369.—Vertical Type Switchboard for Electrically Operated Remote-control Oil Circuit Breakers.

switchboard of the vertical panel type with manually operated oil circuit breakers mounted at the rear of the panels. Figure 369 shows a similar board for electrical remote-control circuit breakers.

It is often found in a large and complex installation that if all the instruments and apparatus were located on a vertical switchboard, its dimensions would be too great for convenient operation, and many appliances, such as control switches, synchronizing and potential receptacles, could not be accommodated in a position most convenient

for the operator. To overcome these difficulties, the bench board has been introduced. In this manner the useful surface has been increased by an amount almost equal to the top of the bench, the latter offering

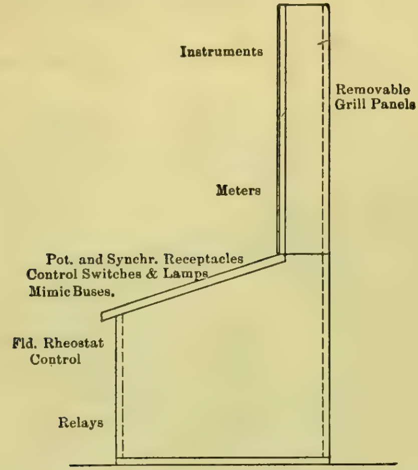


FIG. 370.—A Simple Type of Combination Control Board and Instrument Board Showing the Locations Best Suited for the Various Pieces of Apparatus.

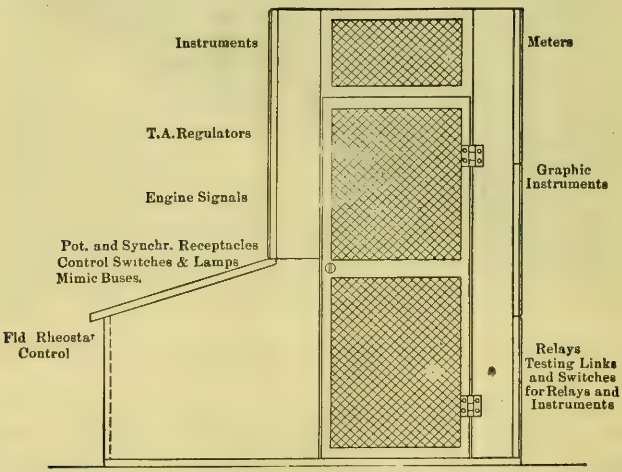


FIG. 371.—An Enlargement on the Arrangement Shown in Fig. 370, which Meets the Demand of Greater Working Surface by the Addition of Rear Panels.

an excellent position for control apparatus, bringing it within distinct view and convenient reach of the operator.

Another advantage is also incidentally obtained, by reason of the

greater distances between the instruments and the operator, which enables him to observe a greater number of instruments from any point

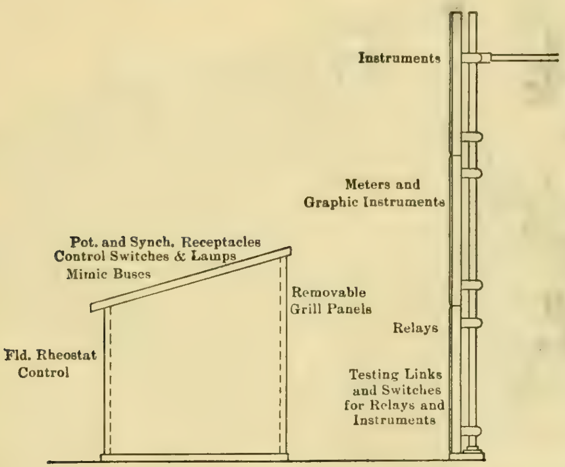


FIG. 372.—Control Board with Independent Instrument Board. This arrangement offers more useful surface than does that of Fig. 370.

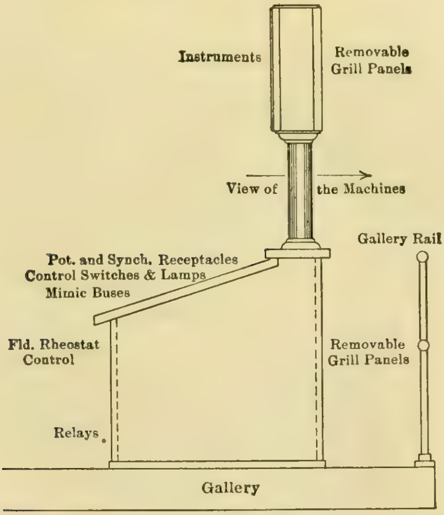


FIG. 373.—A Gallery Type of Bench-board which Permits the Operator Viewing the Machines through the Board.

while manipulating the control apparatus. A further advantage may be taken of this condition by increasing the height of the instrument

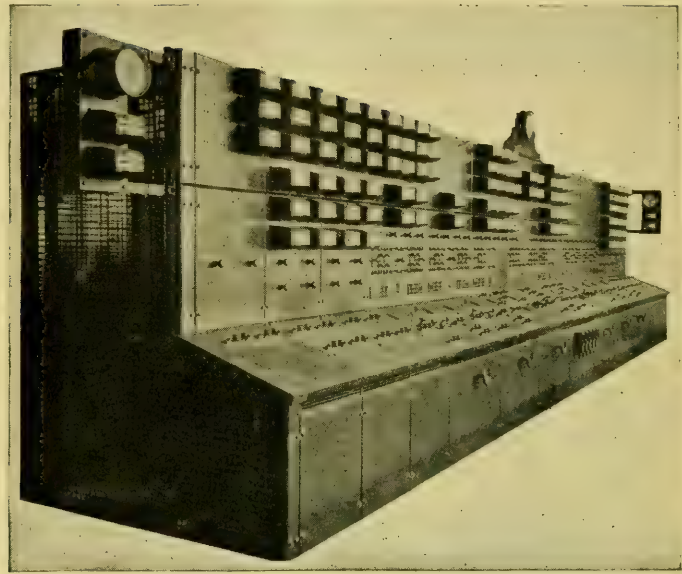


FIG. 374.—Typical Benchboard of the Continuous Type.

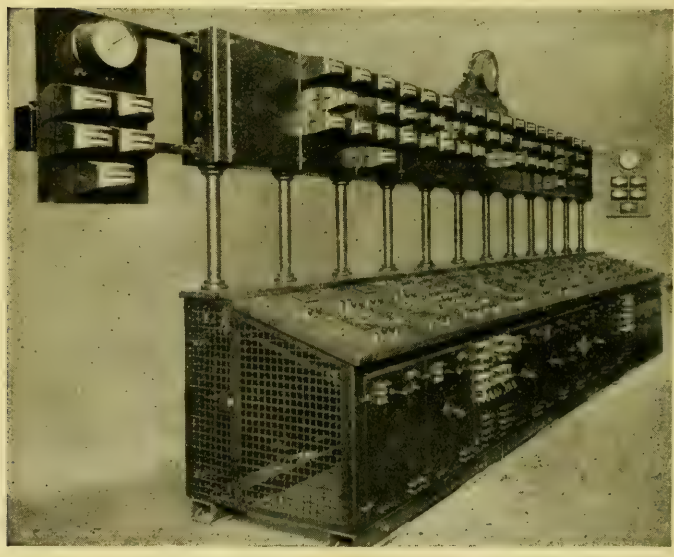


FIG. 375.—Typical Benchboard of the Gallery Type.

section, if desirable, in order to allow room for more instruments, which may be read without difficulty.

Figures 370 to 373 show different types of bench boards in use and the relative locations of the different pieces of apparatus. The choice between the different types depends entirely upon the apparatus involved and on the local conditions. It is thus often found that a bench board of a certain design will give the best result for controlling the machines, while a vertical panel board will be more feasible for feeder circuits. When separating the boards, the number of operators required should always be considered.

FIG. 376.—Mississippi River Power Company. Chief Operator's Room Showing Control Boards and Switchboards.

Pedestal control boards are occasionally used, but there seems to be no real advantage in splitting up the equipment to such an extent. Figures 374 and 375 illustrate two typical bench board designs, and show the improved method of ventilating these boards. Figure 376 shows the control room of the Mississippi River Power Company at Keokuk. The operation in this station is completely controlled by a chief despatcher, who is in telephonic communication with all parts of the system. A special desk is provided for him, on which is mounted the telephone switchboard, while in front of this desk a miniature arc-shaped switchboard is installed which contains a set of mimic busbars

showing, by means of small indicating lights, the open or closed position of all the breakers in the station. It also contains graphic voltmeters and ammeters for recording the voltage on each bus section and the current in each of the outgoing lines.

The main control switchboard is divided into sections corresponding to the bus sections, with an additional section for the auxiliary equipment. The arrangement of these boards is, at the present time, in the form of an L, although ultimately it will be in the form of a U with the despatcher board in the center.

Diffused illumination in the control room is provided by means of a skylight, which forms the entire ceiling. In order to prevent glare on the instruments, it also became necessary to provide amber-colored glass in the windows. At night a diffused illumination is accomplished by tungsten lamps, which are mounted back of the skylight panes.

Instrument Equipment. The instrument and meter equipment for any particular installation should be chosen with the idea of getting something which is satisfactory from an engineering standpoint, at the same time keeping in mind its cost in proportion to that of the total installation, and also considering the class of attendants who will operate the board. It is not good economy to invest in an elaborate set of instruments when the man who operates the plant does not understand their use. In the large installations, where more intelligent help is employed, the efficiency of the plant can be greatly improved by the use of instruments which are understood, but which would be worse than useless in the hands of the unskilled attendant.

Obviously it is difficult to establish exact dividing lines which will cover all conditions. The table in the following paragraphs gives the instrument equipment recommended for use on the circuits enumerated. Special operating conditions and requirements will often demand different measuring apparatus, but the table will, in all cases, serve as a guide in choosing a suitable equipment.

Instruments of each different function are valuable under certain conditions or to aid in accomplishing certain results. To assist in the choice of these and to explain the advantages gained by using each particular instrument, the information in the following paragraphs will be found useful.

For Direct-current Installations. *Direct-current Ammeters.* (1) On machines of all kinds, heating is the factor that determines the load which can be carried safely, assuming the voltage normal. Ammeters give an indication of the heating of circuits in which they are connected, and consequently are indispensable for machine circuits.

(2) They show the division of load between machines.

(3) On feeder circuits they indicate which feeders are overloading the machines, and also furnish a means for indicating the gradual growth or decline in the demands made upon the generating apparatus by any particular feeder, thus giving a warning that the capacity of the apparatus must be changed, or the feeder load rearranged.

Direct-current Voltmeters. (1) They show that the voltage at which machines are being operated is not high enough to damage their insulation, or to damage apparatus for which the machines furnish power.

(2) They are required when machines are to be operated in parallel. Machines must be of the correct polarity and at very nearly the same voltage in order that they may be thrown together with the least disturbance.

(3) They can be used as ground-detecting devices, by making proper connections to the system.

Curve-drawing Instruments. They give a permanent record of the running conditions of the circuits in which they are connected, without the loss of time and possible chance of error which occur when such records are computed from the readings of indicating instruments. Showing, as they do, the distribution of the load for every hour of the day throughout the year, they place in the hands of the management very valuable information which forms the basis for future extensions or improvements of service and load distribution.

For Alternating-current Installations. *Alternating-current Ammeters.* (1) They give an indication of the heating of the armature of the machine. This is a thing which the indicating wattmeter will not do, because of the fact that it measures only the energy component, while the ammeter measures the reactive as well as the energy component of the current, both of which produce heating.

(2) In case machines in multiple are running at the same power factor, ammeters show the division of load.

(3) On feeder circuits, ammeters indicate which feeders are overloading the machine.

(4) On overhead-transmission lines, the use of three ammeters, one in each phase, gives an indication of trouble on the lines, such as grounding.

Alternating-current Voltmeters. (1) They show that machines are being operated at a voltage not too high to damage the insulation, or to damage apparatus for which the machines furnish power.

(2) They are valuable when machines are to be operated in parallel. Machines must be at very nearly the same voltage in order that they may be thrown together with the least disturbance to the system.

(3) They can be used as ground-detecting devices, by making proper connections to the system.

(4) The compensated type, or ordinary type with line drop compensator, is useful to indicate at the power station the voltage at any predetermined point of a feeder.

Direct-current Field Ammeters. (1) They give an indication of the heating in the fields of machines.

(2) They assist in locating trouble in a machine. For instance, in case the alternating-current voltmeter on a generator, which is supposedly operating normally, shows that there is no voltage generated, a glance at the field ammeter may show no reading, in which case it is evident immediately that the field circuit is broken or the exciter system in trouble.

(3) They give an indication of cross currents in generators. For instance, consider a generator panel containing main alternating-current ammeter, power-factor indicator, voltmeter, and field ammeter. If the machine is up to speed, the amount of field current in excess of normal which is required at a given power factor to hold normal voltage, shows proportionately the amount of cross current.

(4) They are of great value in the fields of synchronous motors, because for any given load and power factor the armature current is a minimum for a certain value of the field current for which the field can be adjusted with the aid of the field ammeter.

Indicating Wattmeters. (1) They show the actual power in a circuit, no matter what the power factor, since they measure the energy but not the reactive component. This makes them valuable in the circuits of alternating-current machines operated in multiple, since they show the division of load between machines, something which ammeters alone do not indicate, except when machines are operated at exactly the same power factor and voltage.

(2) In the absence of curve-drawing instruments, they furnish a means for obtaining the load curve of a station.

(3) They indicate reversal of power in a circuit, which an ammeter will not do.

Power-factor Indicators. (1) It is a well-understood fact that it is most economical to operate power plants at as high a power factor as possible, in order to get a maximum output from the machines. The power-factor indicator is very useful in telling directly what this power factor is. Proper wiring arrangements make it possible to use only one instrument per board, plugging it to different circuits. In this way the circuits of poor power factor can be discovered, and steps taken to improve conditions if considered desirable. Where synchronous con-

densers are used for power-factor correction, the power-factor indicator, connected to the bus or circuit to be corrected, becomes particularly valuable.

(2) Generators in multiple will operate at maximum output when they are all running at the same power factor, reducing cross currents to a minimum. The power-factor indicator affords the easiest means of making this adjustment, since it shows the power factor of each machine at a glance, without the necessity of computing this from the readings of other instruments.

(3) The reading of a power-factor indicator in connection with that of an ammeter and voltmeter makes it possible to readily figure the kilowatt output of a machine without the use of an indicating wattmeter.

Reactive Volt-ampere Indicators. (1) They measure the idle or reactive portion of the power and are the only instruments which do so directly.

(2) In connection with the reading of an indicating wattmeter, the readings of the reactive volt-ampere indicator give an easy means for figuring the power factor.

(3) They are considered in some cases more valuable than power-factor indicators, since they are given an actual quantitative reading in kilovolt-amperes, while the power-factor indicator gives a reading in per cent only. This fact can readily be seen from an inspection of the following simple formula:

$$\text{Power factor} = \frac{\text{True watts}}{\text{Apparent watts}}.$$

(Where the apparent watts is the vector sum of the true watts and the reactive watts.) The reading of a power-factor indicator gives no actual indication of magnitude of the idle currents which cause heating. For instance, at light load a power factor of 0.7 or 0.8 would be no cause for alarm, while at full load or overload it might mean serious heating due to idle currents. This is especially true on synchronous converters, where, on account of the rectifying action of such machines, the cross-section of copper is made smaller than in a generator of the same capacity.

Frequency Indicators. (1) Machines operate most economically at the frequency for which they are designed, which makes the use of the frequency indicators evident.

(2) They are valuable when synchronizing machines, since they can be connected on the incoming machine and indicate its speed, showing whether it is too high or too low. However, where a synchronism indicator is installed they are not required for this purpose, since this

instrument shows whether the speed of the incoming machine is high or low.

Synchronism Indicator. (1) The synchronism indicator affords the quickest and safest means for operating machines in parallel, since it shows when the machines are in step and in phase, indicating by the position of the needle the difference in the phase relations between the machines, and telling whether the incoming machine is running too fast or too slow. It is superior to synchronizing with lamps, because the latter give no indication of the relative speed of the incoming machine. The lamps will indicate when the machines are of the same frequency, but the phase relations can be judged only by the brilliancy of the light.

When synchronizing with lamps dark, the phase relation of the machines will be shown by the brilliancy of the light to a point where the machines are approximately 45° out of phase, below which point there will not be sufficient voltage across the lamp to make it glow. Again, in case there is an inopportune failure of the lamp, the operator may be misled and throw the machines together when out of phase with possibly disastrous results.

When synchronizing with lamps bright, it is difficult to determine, after watching the lamps for some time, at just what instant they are burning at full brilliancy, and, therefore, at just what instant the machines are in synchronism.

Synchronizing on high-tension lines, while often desirable, has been out of the question because of the excessive cost and space required for installing the necessary potential transformers for a secondary synchronism indicator. A glow synchronism indicator is now available for this purpose on circuits of 13,200 volts and above. The new indicator depends for its operation upon the principle of electrostatic discharge in a vacuum.

The instrument case resembles the ordinary round pattern switchboard instrument. Inside the case are receptacles for holding the special glowers which project through holes in the cover. Connections from the line to the device are made through condensers, which consist of suspension insulators having an insulation equal to that used on the line. Normally the glowers have the appearance of ordinary spherical frosted incandescent lamp bulbs. When, however, there is a proper difference of potential across their terminals, they will glow with a reddish hue. When the lines are not in synchronism, the glowers will light up in succession, showing the relative direction of rotation and indicating whether the incoming machine is running fast or slow. When synchronism is reached there will be no rotating effect, and one glower will be dark while the other two will glow at about half brilliancy.

Electrostatic Ground Detectors. (1) They give a constant indication of the condition of the system with respect to grounds, which, if not detected immediately, often result in very serious burn-outs or voltage disturbances.

(2) They are superior to any system of ground detecting which necessitates the plugging of potential transformers and lamps or voltmeters to different phases of a polyphase system; first, because the polyphase electrostatic ground detector shows, at a glance, whether there is a ground on any phase, while with the other scheme it is necessary to plug the primary side of the transformer to the different phases before the test is completed; and, second, because the electrostatic ground detector is supplied with a scale for reading the severity of the ground, while with lamps only an approximate indication is obtained ordinarily, and for high resistance grounds no indication whatever, since the ordinary 125-volt carbon lamp will not glow at much less than 25 volts across its terminals.

Temperature Indicators. (1) It is of great value to know the temperature of certain parts of generator and transformer windings that are inaccessible for thermometer measurements. An instrument known as the temperature indicator has been produced to determine these temperatures. Copper coils of known resistance are placed in the parts whose temperature it is desired to know. The changes in resistance are shown on the scale of the indicator, which is marked in degrees Centigrade corresponding to the change in resistance.

When a direct-current source of supply is available, the indicator consists of a differential voltmeter with the scale marked in degrees Centigrade, corresponding to the change in resistance. When an alternating-current source of supply only is available, as in transformer stations, the indicator consists of a dynamometer with the scale marked in degrees Centigrade, corresponding to the change in resistance.

Curve-drawing Instruments. (1) They give a permanent record of the running conditions of the circuits in which they are connected, without the loss of time and possible chance of error which occur when such records are computed from the readings of indicating instruments. Showing, as they do, the distribution of the load for every hour of the day throughout the year, they place in the hands of the management very valuable information which forms the basis for future extensions or improvements of service and load distribution.

The following table gives the instrument equipment usually employed for use on the circuits enumerated. Each circuit is considered a complete unit in itself. A combination of two units does not mean that all instruments listed for each separately will be used on the combination.

For instance, where a generator and transformer are permanently connected together and operated as a unit, there is no necessity for using an ammeter in the transformer circuit, since it would simply duplicate the reading of the generator ammeter. Other similar cases are numerous, such as combined generator and feeder circuit, combined transformer and feeder circuit, etc. Special operating conditions and requirements will often demand different measuring apparatus from that given, but the table will at least serve as a guide in choosing a suitable equipment in all cases. The small letters in the table refer to the notes following the table.

CURRENT AND POTENTIAL TRANSFORMERS

When the voltage or current of the circuit to which instruments, meters, and relays are to be connected exceeds a certain value, potential and current transformers are employed, the instrument and relay coils being operated from the secondaries of these transformers. In order also to reduce the voltage on the wiring on the rear of switchboard panels, which necessarily must be closely grouped, the use of voltage and current transformers is recommended for all instruments, meters, and relays connected to circuits over 150 volts A.C.

Since the normal rating of the secondary of current transformers is usually 5 amperes, secondary current coils are ordinarily wound for this capacity. When, with a certain capacity of current transformer determined by the load of the circuit, the scale of the instrument would be too large to allow a good reading at light loads, 4-ampere windings may be used in the instrument, the scale then being about 80 per cent of that corresponding to that used with the 5-ampere winding. Secondary potential coils for instruments and relays are ordinarily wound for 110 volts, the voltage of the secondary side of standard potential transformers.

Instruments may be operated from the same current transformers that are used with the oil-circuit-breaker trip coils or relays, provided the volt-ampere secondary burden is such that the accuracy of the instrument and transformer combination comes within certain set limits. Wattmeters and watthour meters, however, should not be used on the same current transformers with certain devices which have current and potential windings in an inductive relation which may cause phase-angle variations. Among such devices are certain types of differential or reverse power relays, compensated voltmeters (indicating or contact-making), or line-drop compensators.

The same potential transformers can also be used for operating

TABLE LI

DIRECT CURRENT

Circuit Measured.	Name and Number of Instruments Used.	
	Ammeter.	Voltmeter.*
Two-wire generator	1	1 per switchboard plugged to each generator
Two-wire exciter generator	1	(*d*)
Brush arc generator	1 (Plugged to read each machine circuit)	None required
Two-wire feeder	1 (*a*)	None required ordinarily
Railway feeder	1	Plug to station voltmeter to read trolley voltage
Two-wire battery †	1 (Zero center)	1 plugged to read battery and bus voltage
Two-wire synchronous converter	1	1 per switchboard plugged to each machine
Two-wire motor	1 (*b*)	None required
Three-wire generator	2 (One in positive and one in negative lead)	1 per switchboard plugged to read voltage between outside wires of each machine
Three-wire feeder	2 (One in positive and one in negative lead)	None required ordinarily
Three-wire synchronous converter	2 (One in positive and one in negative lead)	1 per switchboard plugged to read voltage between outside wires of each machine
Three-wire balancer	1 (Zero center) (connected in neutral)	1 plugged to each machine of the balancer set

(*a*) On multiple-circuit feeder panels controlling feeders of small capacity, ammeters are usually omitted.

(*b*) On small motors, ammeters are usually not furnished.

(*d*) Where there are only two exciters operating in parallel, one voltmeter is used on each exciter equipment. Where there are three or more exciters, two voltmeters are employed and mounted together on a swinging bracket at the end of the board, usually on the same bracket containing the alternating current voltmeters and synchronous indicator. One is connected to the bus and the other is arranged to be plugged to any machine to read voltage at any time. In many instances exciters are direct-connected or belted to the alternating-current machines, the fields of which they excite, and are not operated in parallel, no separate panels being furnished to control them. In such cases no measuring instruments are furnished, the field ammeter of the alternating-current machine taking the place of the exciter ammeter, while there is ordinarily no use of the voltmeter.

* Where the different types of circuits given in the first column occur in the same board, only one voltmeter need be supplied, provided the scale is suitable for the voltage of all circuits to be measured.

† Owing to the large number of methods of connecting batteries, no definite instrument equipment can be listed to apply to all cases. The above represents a simple equipment for measuring charging and discharge current and voltages as indicated.

TABLE LI—*Continued*

ALTERNATING CURRENT

GENERATORS, MOTORS AND SYNCHRONOUS CONVERTERS

Circuit Measured.	Name and Quantity of Instruments Used					
	A.C. Ammeter.	A.C. Voltmeter.	Indicating Wattmeter.	Field Ammeter.	Reactive Volt-Ampere Indicator.	Misc.
3-phase, 3-wire generator, below 500 Kw., balanced load	1	(*d*)	...	1	...	(*c*) (*e*)
3-phase, 3-wire generator, 500 Kw. and over, balanced load.	1	(*d*)	1	1	...	(*c*) (*e*)
3-phase, 3-wire generator, unbalanced load, or 3-phase, 4-wire generator	3 (or 1- and 3-way transfer switch)	(*d*)	1	1	...	(*c*) (*e*)
3-phase, 3-wire generator, railway service	1	(*d*)	1	...	1	(*f*) (*c*) (*e*)
2-phase, 4-wire generator, below 500 Kw	2 (or 1- and 2-way transfer switch)	(*d*)	...	1	...	(*c*) (*e*)
2-phase, 4-wire generator, 500 Kw. and over	2 (or 1- and 2-way transfer switch)	(*d*)	1	1	...	(*c*) (*e*)
3-phase, 3-wire or 2-phase, 4-wire synchronous motor	1	(*g*)	...	1	...	(*c*) (*e*)
3-phase, 3-wire or 2-phase, 4-wire synchronous condenser *	1	(*h*)	...	1	(*k*)	(*k*) (*e*)
3-phase, 3-wire or 2-phase 4-wire induction motor	1	...	...	...	...	(*e*)
Synchronous converter with step-down transformers (power and lighting)	1 (connected in high tension side)	...	...	...	...	(*c*)
Synchronous converter with step-down transformers (rwy.)	...	...	...	...	1 (connected next the conv. rings)	(*c*)

* Used for regulation of power-factor and voltage.

TRANSFORMERS AND FEEDERS

Circuit Measured.	Name and Quantity of Instruments Used.		
	Ammeter.	Voltmeter.	Misc.
3-phase, 3-wire transformer,* balanced load	1	(*n*)	(*c*)
3-phase, 3-wire transformer,* unbalanced load	3 (or 1- and 3-way transfer switch)	(*n*)	(*c*)
3-phase, 4-wire transformer *	3 (or 1- and 3-way transfer switch)	(*n*)	(*c*)
2-phase, 4-wire transformer *	2 (or 1- and 2-way transfer switch)	(*n*)	(*c*)
Constant-current transformer	1 (in secondary side of transformers)	...	...

3-phase, 3-wire feeder (transmission line)	3 (or 1- and 3-way transfer switch)	(n)	(c)
3-phase, 3-wire local feeder, balanced load	1	....	....
3-phase, 3-wire local feeder, unbalanced load	3 (or 1- and 3-way transfer switch)	....	....
3-phase, 3-wire feeder, balanced load with one feeder voltage regulator	1	(o)	....
3-phase, 3-wire feeder, unbalanced load with one feeder voltage regulator	3 (or 1- and 3-way transfer switch)	(o)	....
3-phase, 4-wire feeder	3 (or 1- and 3-way transfer switch)	....	....
3-phase, 4-wire feeder, with three feeder voltage regulators	3 (or 1- and 3-way transfer switch)	(p)	....
Single-phase, 2-wire feeder, with one feeder voltage regulator	1	(o)	....
2-phase 4-wire feeder, balanced load	1	....	....
2-phase, 4-wire feeder, unbalanced load	2 (or 1- and 2-way transfer switch)	....	....

* May be a bank made up of single-phase transformers or a single polyphase transformer.

(c) When it is necessary to connect in parallel two sources of power, such as two generators, or a generator and an incoming line, a synchronism indicator is used. One instrument per board is required for each frequency, with the proper arrangement for plugging to the different circuits. It is ordinarily mounted on a swinging bracket at the end of the board.

(d) Where there are only two generators, one voltmeter is used on each generator equipment. Where there are three or more generators two voltmeters are employed and mounted together on the swinging bracket containing the synchronism indicator. One is wired in multiple with that coil of the synchronism indicator which is connected by the synchronizing plug to the running machine and is cut out during normal operation. The other is arranged to be plugged to any machine to read voltage at any time.

(e) A temperature indicator is required by the Standardization Rules of the American Institute of Electrical Engineers on all stators of machines having cores 20 inches wide or over, and on all machines of 5000 volts or over, if over 500 Kv.A. (750 H.P.) in capacity regardless of core width.

(f) In addition to the equipment given, a watt-hour meter is also furnished for each generator.

(g) A voltmeter is required when the motor is brought up to speed mechanically and it is necessary to synchronize with the source before throwing it in circuit.

(h) Use one voltmeter to read voltage on line regulated. (Can use voltmeter called for in (d) if in same switchboard.)

(k) The reactive component indicator connected in the machine circuit and the power-factor indicator connected in the line to be regulated are very often employed. The synchronous condenser, in itself, had a tendency to regulate the voltage, but a voltage regulator is recommended in connection with it.

(n) A voltmeter is used only when it is necessary to synchronize with the source to which the machine or feeder is to be connected. Voltmeter as called for in (d) can be used if in same switchboard.

(o) Use either one compensated voltmeter (to take care of ohmic drop) or one standard voltmeter with a separate compensator (to take care of inductive as well as ohmic drop).

(p) Use either three compensated voltmeters (to take care of ohmic drop) or three voltmeters with their separate compensators (to take care of inductive as well as ohmic drop).

instruments and potential coils of relays, low-voltage release, or other apparatus, as long as the rated volt-ampere secondary burden of the transformer is not exceeded. This burden and its power factor must be clearly distinguished from the load and power factor of the main circuit, which are measured by the measuring outfit of which the instrument transformer is a part.

The " secondary burden " of a current transformer is an expression of the resistance and reactance of the external circuit connected to its secondary. It is usually given in volt-amperes based on a 5-ampere secondary current.

The volt-ampere of the various secondary devices, such as indicating instruments, meters, relays, etc., varies considerably and should be obtained from the manufacturer.

In view of the fact that meters, as well as current transformers, show a comparatively low accuracy at low load factor, it is objectionable to use current-transformer combinations with normal currents considerably below the rating of the current transformer. A current transformer should, furthermore, under no consideration be used on primary current in excess of its rating, except momentarily, as the permissible heating limit of current transformers coincides practically with the current rating of the transformer. Where the primary current imposed on current transformers during short circuits is likely to cause excessive over-heating or electromagnetic stresses with standard-wound primary-type current transformers, the best practice is to use separate current transformers of the one-turn primary or busbar type for the protective devices, even though the circuit rating is considerably below the current-transformer rating, so that in case of short circuits, etc., the destructive effect is limited to the transformers for the meters and instruments and does not jeopardize the protection of the system. In this manner, safety of operation will be combined with accuracy of metering.

At frequencies below the rated frequency, current transformers can be operated with their normal accuracy, but the secondary load must be reduced considerably below the load permissible for the rated frequency of the transformer. With frequencies somewhat above normal, the accuracy of the transformer will not be impaired, but the reactance drop through the transformer may be increased materially, and its effect on the regulation of the circuit in which it is connected should be considered.

Certain types of oil circuit breakers are so constructed that bushing-type current transformers can be used if desired, the bushing support providing a suitable housing and protection for the transformer. They

can be mounted on either or both bushings of a single-pole circuit-breaker unit, and may be used for tripping purposes and for operating an ammeter. It is not recommended, however, that the trip coils and the ammeter be operated from the same bushing transformer, on account of the limited volt-ampere capacity of a bushing transformer and because any change in the trip coil setting may affect the accuracy of the ammeter reading.

On account of the necessarily great length of the magnetic circuit, and the fact that only one primary turn can be provided, the magnetizing current must be high, and accordingly the transformers are rather inaccurate for the lower ratios. However, as most operating companies now relay for short-circuit protection, there is seldom any need for using these low ratios. A bushing transformer of a ratio 150/5 amperes will give good results when used with relays. As the ratio increases the errors decrease, and by the time a ratio of 300/5 amperes is reached the bushing transformer is equal in most and superior in some respects to the standard instrument type of current transformer for protective relay purposes. Ratios of less than 150/5 amperes are not recommended for the various balanced relay schemes, and even at this value it is preferable to connect the secondaries of two transformers in series. A ratio of 200/5 amperes usually gives satisfactory results with a single transformer for balanced work.

Where a low tripping point is desired and the tripping current is supplied by use of bushing-type current transformers, it is recommended that a single-circuit circuit-closing induction-type overload relay be used. These relays can be equipped with a 1 ampere coil and therefore are very sensitive for low current values.

Circuit-opening relays, on the other hand, should never be used with bushing current transformers, on account of the burden imposed on the transformers of not only the relay coil but also the trip coil.

The secondaries and cases or frames of current transformers should be grounded whenever possible. The switchboard wiring should be carefully considered, to see if this can be done without interfering with the proper operation of the instruments connected to the transformers. The grounding of the cases serves the double purpose of protecting the switchboard attendant and freeing the instruments from the effects of electrostatic charges which might otherwise collect on the cases and cause errors.

The primary of current transformers should never be left in the line with the secondary open-circuited, as this will set up a heavy flux through the core, over-saturating the iron and causing it to overheat greatly. If for any reason, therefore, it becomes necessary to remove

the meter or any current-carrying device from the secondary circuit of a current transformer, the secondary should be short-circuited by a wire or some other means.

By-pass protective devices are occasionally provided across the primary terminals of current transformers, to take care of high-frequency surges and to reduce the voltages across these terminals caused by the high-frequency current.

Potential transformers are used to insulate instruments, meters, and relays from high-voltage circuits and to eliminate large amounts of resistance which would otherwise have to be connected in series with these if they were connected directly to the high-voltage circuit.

It is generally permissible to operate a potential transformer with a voltage variation at normal frequency of ± 10 per cent, without any appreciable loss of accuracy. This does not imply, however, that a potential transformer should be used on circuits rated 10 per cent above normal, where the actual voltage due to line drop may cause the transformer to be subjected to a voltage as high as 20 per cent above its rating.

The standard secondary voltage of potential transformers is 110 volts, and the volt-ampere capacity, as given by the manufacturer, is generally based on this value. If furnished with a secondary voltage other than 110 volts, the volt-ampere burden of the individual devices should be modified in accordance with the difference in potential, the actual volt-ampere burden being equal to $\left(\frac{V}{110}\right)^2$ times the volt-amperes at 110 volts, where V is the special voltage.

Potential transformers, when used with instruments, meters and relays, should not be loaded in excess of their rated volt-ampere capacity. This rated capacity is, in most cases, considerably below the capacity which the transformer could carry without overheating and is chiefly governed by considerations of accuracy.

Primary fuse protection is recommended for potential transformers up to 22,000 volts. Above this they are not generally furnished. Current-limiting resistors in series with the primary fuses are also recommended for use on large systems, since they limit the short-circuit current to a value which the fuse can safely interrupt.

Current and potential transformers are either air-cooled or oil-cooled, depending on the voltage. They are now also designed for indoor or outdoor installation.

The connections for the multitude of instruments, meters, relays, etc., with their current and potential transformers, which are used in the modern power station are very intricate. While for individual

equipments such connections may be standardized, the combinations used in a large station are generally such as to make the connections more or less special, in order to give the best results. Individual diagrams are, as a rule, contained in the bulletins issued by the various

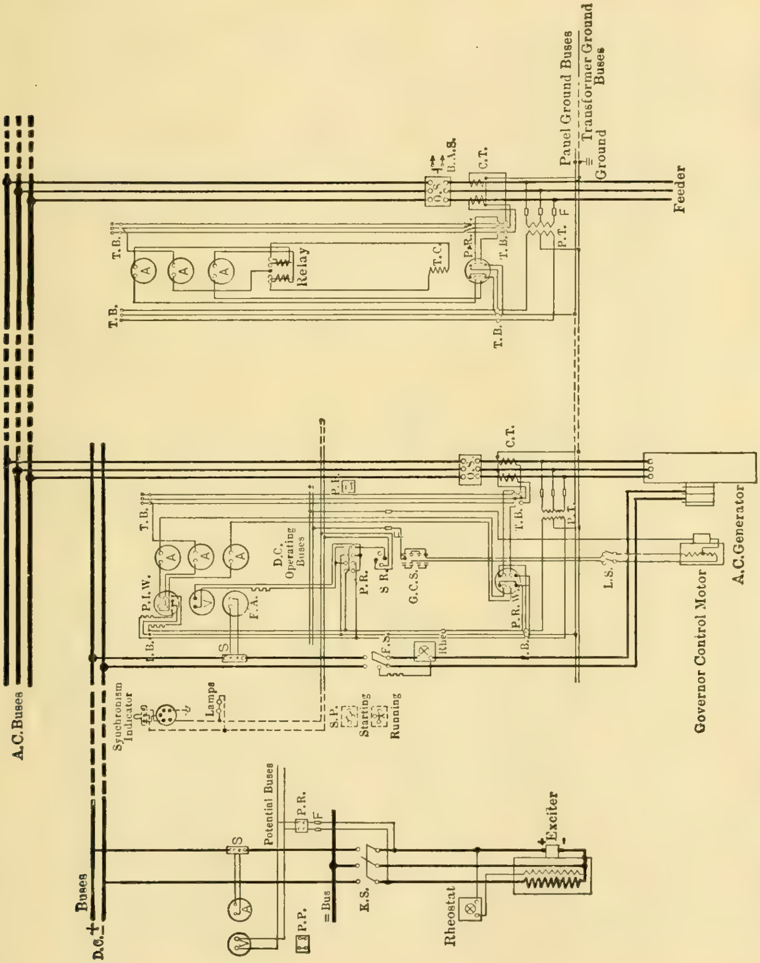


FIG. 377.—Diagram of Connections for the Control of Exciter, Generator and Feeder.

manufacturers, and the making up of the main wiring diagram for any important installation should be left to the manufacturer supplying the switchboard. A typical diagram of connections for an individual exciter, an A.C. generator, and an outgoing feeder is shown in Fig. 377 as an example.

Key to Symbols

A. = Ammeter.
B.A.S. = Bell-alarm switch.
C.T. = Current transformer.
F. = Fuse.
F.A. = Field ammeter.
F.S. = Field switch.
G.C.S. = Governor-control switch.
K.S. = Knife switch.
L.S. = Limit switch (included with governor motor).
O.S. = Oil circuit breaker.
P.I.W. = Polyphase indicating wattmeter.
P.R.W. = Polyphase watthour meter.
P.R. = Potential receptacle.
P.P. = Potential plug.
P.T. = Potential transformer.
Rheo. = Rheostat.
S. = Shunt.
S.R. = Synchronizing receptacle.
S.P. = Synchronizing plugs.
T.B. = Terminal board for secondary leads from current and potential transformers.
T.C. = Trip coil on oil switch.
V. = Voltmeter.

Exciter and Field Control. For the electrical control of exciter circuits it is usual to omit fuses or other overload devices, in order to prevent any interruption in the supply of field current to the alternating-current generators, thereby insuring continuous operation, which, in most stations, is an essential feature and is of more importance than protection of the exciters from damage. This omission is also an insurance against injury to the alternating-current generator field windings. When trouble occurs in the exciting system and opens the overload devices on all the exciters connected, the generator field circuits are broken at points where no discharge resistances are interposed, and the generator field windings are consequently liable to puncture by the high induced voltage to which they are subjected. If overload protection is insisted upon, it is recommended that the overload devices, fuses or circuit breakers, be based on double the normal capacity of the exciter, so as to open only in case of very serious trouble.

For large plants having a number of exciters in parallel, and where the expense involved is of secondary consideration, it is customary to provide reverse-current circuit breakers without any overload at-

tachment. The reverse-current device serves to disconnect a defective exciter while the remaining exciters continue in service.

Circuits for motors driving exciters are usually considered as feeder circuits, and overload protection is accordingly recommended for the motor. A time-limit device is preferable for this overload feature, and, if an instantaneous device is used, it should be set very high. When operating conditions make it necessary, the overload feature can be very readily disconnected. With motor-driven exciters operating in parallel, it is also advisable to equip the exciter circuits with reverse-current circuit breakers, so as to prevent any set which might be disconnected from the bus on the motor side from continuing to operate by its exciter running as a motor and taking power from the exciter bus. The D.C. breaker could, of course, also be provided with a shunt trip arrangement whereby the opening of the A.C. oil circuit breaker would in turn trip the D.C. breaker.

For small and medium-sized installations, the exciter switches are usually of the ordinary knife-switch type mounted directly on the main switchboard. For large installations it is, however, common practice to employ solenoid-operated carbon-break circuit breakers. These are often mounted on panels near their respective exciters, so as to reduce the length of connections to a minimum, and controlled from the main board.

Occasionally a separate direct-current switchboard is provided and located at some convenient place near the exciters. On this board are then mounted all the exciter and field switches, as well as other low-voltage switches and circuit breakers for the various station circuits.

Field switches for disconnecting the individual fields of the A.C. generators should always be provided. These switches are known as "field discharge switches" because their design is such that when they are opened a discharge resistance is automatically inserted in series with the field circuit. If this should be suddenly broken, an excessively high potential would be induced in the field winding, and might puncture its insulation. When a resistance is inserted in the circuit, the E.M.F. induced in the field coils by the dying magnetic flux produces a current through this resistance; thus, the energy stored up in the magnetic field when the current was compelled to increase against the induced counter E.M.F., is now discharged in this resistance where it appears as heat. The construction of the switch is such that when it is opened the resistance circuit is closed before the field is disconnected from the exciter or field bus, while, when it is closed the resistance circuit is opened before the field is connected to the exciter. By this means all destructive arcing is also avoided, for the field can never be broken without shunting it through the discharge resistance. Certain

types of switches are, on the other hand, provided with a stop so that they cannot be completely opened until this has been withdrawn, thus giving the induced field energy time to be dissipated through the discharge clip to the discharge resistance before the circuit is broken.

Field switches, like exciter switches, may be either hand operated or solenoid operated. In the former case they may be identical with ordinary knife switches, to which discharge clips have been added, and which have been mounted on the front of the panel. It is becoming very general practice, however, to mount the live part back of the switchboard and operate it by a handle from the front of the board. This type of field switch is regarded as a " safety first " device of great importance and is to be recommended in all cases. The switchboard attendant cannot come in contact with the live parts or arc when operating, and instruments and other adjacent equipment are safe from damage by burning, which occasionally happens with the front-of-board type.

With bench-board equipments and with large capacity vertical switchboards where remote control is desirable, solenoid-operated field switches are often employed. While controlled from the main board, they may be located at the most convenient point, for example, near the generators or on the exciter board. They are similar in construction to the non-automatic, self-contained, solenoid-operated, air circuit breaker, with the addition of a discharge switch.

A.C. generators and synchronous motors forming part of motor-generator sets having either 125- or 250-volt field excitation, and all other synchronous motors having 250-volt excitation, which are commonly started with the field short-circuited, should be provided with double-pole field switches, and the field should be short-circuited through the discharge resistance. This prevents any high induced voltage across the collector rings of the motors. Double-pole solenoid-operated switches are provided with common opening and common closing coils (Fig. 378).

Synchronous motors with 125-volt excitation, not forming part of motor-generator sets, are generally started with the field open-circuited, in which case there is a very high induced voltage across the field until synchronous speed is reached. To avoid danger to the operators in such cases the field switches may be mounted, as previously mentioned, on the back of the switchboard, but operated from the front by means of an operating handle. If the field switch is mounted on the front of the board, as is sometimes done on small isolated panels, protection may be obtained by means of barriers on each side of the switch. Double-pole solenoid-operated field switches may in this case be made

as two single-pole elements with independent opening and closing coils, both units, however, closing simultaneously. When opening, one switch precedes the other by a short time interval, during which the discharge resistance is connected across the field. Then, when the switch in the other pole opens, the discharge circuit is interrupted, the time delay being accomplished by a time-limit relay actuating the switch.

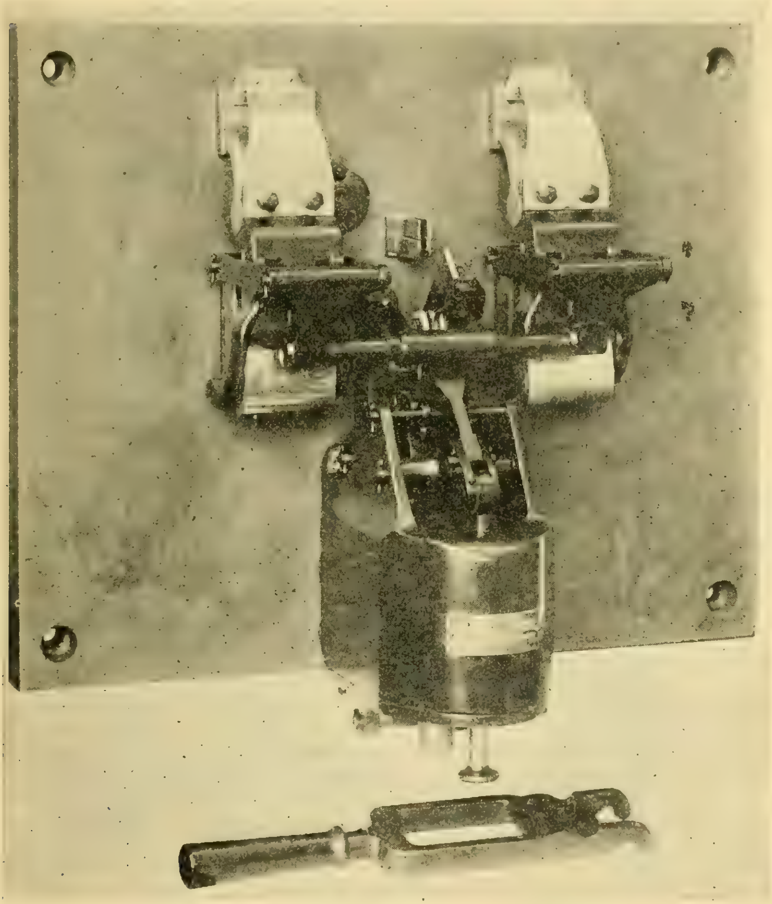


FIG. 378.—Solenoid-operated Field Switch.

In certain instances it may be possible to simplify this equipment of solenoid-operated field switches for 125-volt excited synchronous condensers and frequency changer sets; provided it is satisfactory to start with the field short-circuited through the discharge resistance, in the same manner as for motor generator sets and motors with 250-

volt excitation, previously described. This will probably mean an increase of 15 per cent to 20 per cent in starting kv.a., which in many cases may be negligible in comparison with the capacity of the system to which the machine is connected.

The operating mechanism of field rheostats depends on their size, which also governs their location. The smallest sizes, up to about 25 or 30 amperes, can usually be mounted directly back of the board, and it is only necessary to extend the shaft of the rheostat and connect it directly to the handwheel on the front of the panel. Concentric handwheel mechanisms are also very common, one of the wheels being

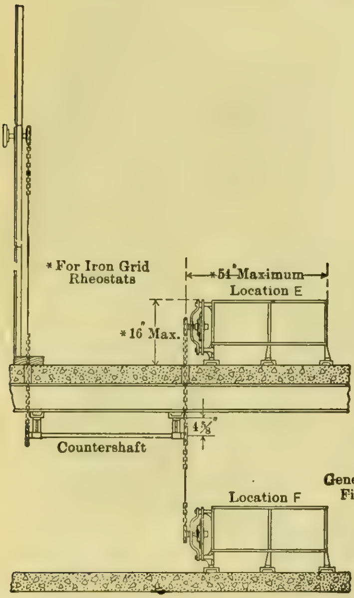


FIG. 379.—Sprocket-wheel Chain Drive for Field Rheostats.

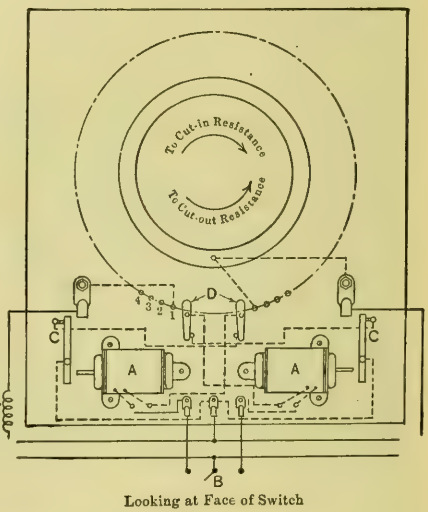


FIG. 380.—Connections of Solenoid-operated Ratchet-driven Field Rheostat Switch.

for the exciter field rheostat and the other for the main generator field rheostat. Such arrangements permit of quite a saving in the space required.

For larger sizes it becomes necessary to mount the rheostats remote from the switchboard, in the basement or elsewhere. The operating mechanism may then consist of a sprocket-wheel chain drive, operated by a handwheel on the front of the board, or it may be electrical, either in the form of solenoids or motors controlled from the main board. A typical arrangement of a sprocket-wheel chain drive is shown in Fig. 379, but it is, of course, evident that the rheostat proper can be located

in many different positions. This class of control is generally limited to rheostat capacities of about 300 amperes or lower.

In many installations it is, however, not possible to locate the rheostat so that the dial switch can be operated by means of chain drive from a hand-wheel on the panel. For such conditions the rheostat can be equipped with a solenoid-operated ratchet switch (Fig. 380), which

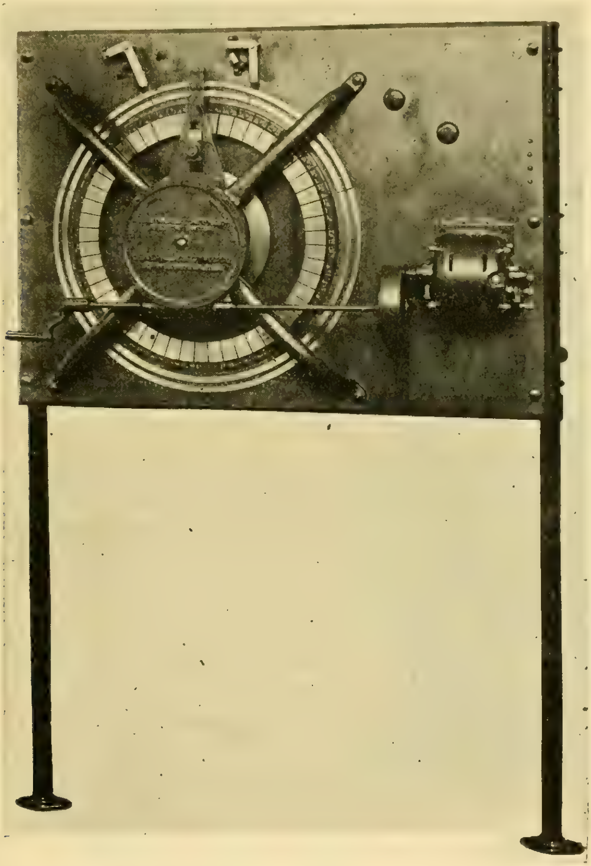


FIG. 381.—Electrically Operated Motor-driven Rheostat.

can readily be controlled from the main board, and the rheostat proper can be located in any part of the station. The limit of capacity is the same as for the chain-operated type, i.e., about 300 amperes, and the operation is as follows:

The switch arm is carried around by pawls which engage the knurled rim of a wheel to which the switch arm is rigidly fastened.

These pawls are controlled by a core actuated in common by the solenoids AA. When the solenoids are de-energized the pawls are disengaged and, in their normal position, rest equidistant from the solenoids. To cut resistance into the field, it is necessary to close to the left the single-pole switch B. This energizes the left-hand solenoid, engages the left-hand pawl and moves the dial switch in a clockwise direction. When the solenoid core has reached its extreme point of travel, the winding of the solenoid is automatically open-circuited by the small switch C, and the pawl is immediately pulled to its neutral position by a spring, automatically closing the circuit of the solenoid switch by the small switch C. The same cycle of operation is then repeated until the switch B is opened. If it be desired to cut resistance out of the field circuit, the single-pole switch B is closed to the right, when the same cycle of operation is performed and the dial switch moves in a counter-clockwise instead of a clockwise direction. Each end of the switch dial is provided with a limit switch, D, which is automatically operated by the switch arm to open the circuit of the solenoid when the resistance is entirely cut in or out. The purpose of the limit switch, D, is simply to protect the apparatus in case the controlling circuit is left closed when the dial switch has reached its extreme point of travel in either direction.

For circuits above 300 amperes the motor-operated type of rheostat (Fig. 381) is the most practical, as the heavy contact on the dial switch is not easily overcome with the solenoid or hand-wheel control. The motor is of the series type with a field winding enabling the dial switch to be operated in either direction by the control switch on the main board. As with the ratchet-driven type, each end of the switch dial is provided with a limit switch, which is automatically operated by the switch arm to open the motor circuit.

Voltmeter and Synchronizing Receptacles. These are devices which provide a ready means for connecting a voltmeter to any machine or any phase of the same, and thus reduce the number of instruments required. They are also used for making the necessary connections at the time of synchronizing. The contact elements are of brass and come through the panel to the front, but are countersunk in a hard rubber escutcheon plate, which makes accidental contact very unlikely. The plugs have brass contacts supported by a hard rubber shield, which also serves as a protection to the hand.

As will be noted from the diagram of connections (Fig. 377), eight-point voltmeter receptacles are provided for the A.C. generator, so that the voltage across all the three phases can be read in turn when the plug is inserted.

With the synchronizing scheme, as shown in Fig. 377, the synchronizing is actually done between the machines. For this reason two plugs are required, one of which is inserted in the receptacles of one of the machines which is running, and the other in the receptacles of the machine which is to be started and synchronized. In large stations, the synchronizing is often done directly between the machine and the bus.

Ammeter Transfer Receptacles. These are for reading the current in any of three phases on one ammeter, by changing the connections from the front of the panel. Each unit of a group consists of a brass plug switch receptacle with fiber insulation, with contacts back of the panel and with a molded bushing on the front. For reading the current, the transfer plug is inserted in rotation in each of the three receptacles of a group. Between such readings the plug can be left inserted in one receptacle, thus giving a continuous indication on that phase.

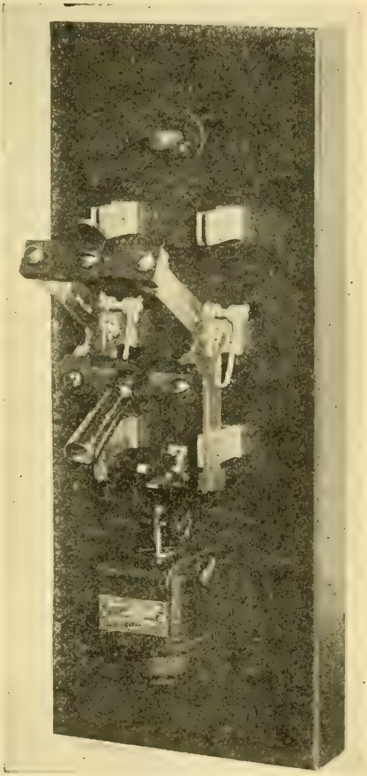


FIG. 382.—Automatic Throw-over Switch.

Throw-over Switches. A sudden failure of the source of power for the lighting system in the power station is a more or less frequent and troublesome occurrence. To take care of such an emergency and facilitate the re-establishment of normal conditions where apparatus may have been shut down through the failure of power, a switch for automatically throwing the lights to an auxiliary or reserve source becomes very handy. The switch shown in Fig. 382 accomplishes this result. The device consists of a special double-throw switch held closed by a latch on one throw against a pair of springs.

To close the lighting circuit, with the normal source of power in operation, the switch is thrown in the lower set of contacts and latched in the closed position by hand. When a failure of the source occurs, a low-voltage release is caused to drop its armature, tripping the latch

free from the crossbar above it. The springs on the hinge clips of the switch then quickly force the switch into the upper set of contacts, which are connected to the reserve source of power. At the same time an auxiliary switch at the top is thrown into contact, causing a bell or other indicator to operate, to attract the station attendant's notice. After the resumption of normal conditions, the switch must be thrown by hand into the lower contacts, and latched.

Calibrating Terminals. A quick and convenient method of making connections for calibrating instruments, etc., is very desirable, and this has led to the very general use of calibrating terminals on all important switchboards. These may be mounted either on the front or back of the panels, the choice being governed by the conditions. For example, where it is difficult to carry on such tests on the back of a board, the terminals may readily be mounted on the front, while if there is plenty of room in the rear, it may be advantageous to locate the calibrating terminals there in order to utilize the space on the front otherwise.

The terminals for the current transformer connections should be such that the testing instrument can be connected in the circuit without breaking the continuity of the circuit, as explained under "Current Transformers."

Control Switches. Remote electrically operated oil or air circuit breakers are controlled by small double-throw control switches, usually mounted on the main switchboard. However, since the energizing current of the operating mechanism may be considerable, in the case of the closing coil of solenoid operated breakers, it is not customary to rely on the control switch for breaking this current, and an intermediate control relay (Fig. 364) is provided for this purpose. The operating coil of this control relay is then connected across the closing contacts of the control switch and the relay contacts in series with the motor circuit or the solenoid closing coil (Fig. 383).

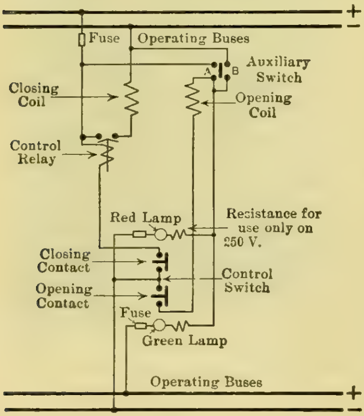


FIG. 383.—Connection for Control Switch for Direct-current Solenoid-control Circuits.

Control switches should always be designed so that all connections may be made on the back of the panel, and so as to render it impossible to operate by accidentally leaning against the switch. This is accom-

plished in the "pull-button" type, which has the contacts on the back of the panel, with pull rods brought through the panel to the handles on the front (Fig. 384). The switch returns to the open position by means of a spring, and both throws (closing and opening) are interlocked. It is provided with a mechanical device to indicate which throw was last closed and, in addition, with red and green bull's-eye lamps to indicate the actual position of the circuit breaker. The necessary auxiliary switches for these lamps are provided with the breaker.

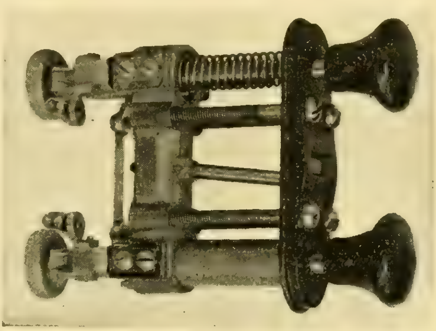


FIG. 384.—Single-pole, Double-throw Pull Button Control Switch.

Mimic Buses. Mimic buses and connections are placed on the front of switchboards or bench boards, usually where remote-control electrically operated equipment is involved, to visualize the system of main connections. They are recommended when the function of control switches for the main circuit breakers will not be clear from their position on the panel, or when, because of the use of many switches on the panel, there might be confusion in quickly finding the proper button to operate.

Mimic disconnecting switches are occasionally required to indicate the position of selector or bus sectionalizing switches in the main connections, but need not be provided if the switches are in series with a circuit breaker, since the lamps for the control switch are a sufficient indication to the operator. It must be recognized that the indication of the mimic switches is dependent on the setting made by the operator and therefore, does not constitute a positive proof of the position of the main switch.

Figures 369 and 374 illustrate the use of such mimic buses.

Bus and Switch Structures. As previously stated, busbars or electrically operated oil circuit breakers are not necessarily placed near the controlling switchboard, but should be placed with regard to convenience of connections and safety from fire and in handling.

Isolating barriers or compartments are recommended for voltages up to 15,000 where the capacity is above, say, 5000 kw., in order to prevent any destructive effects of short-circuits from spreading and involving the entire bus structure.

Furthermore, the compartments act as a guard against anyone

touching the exposed parts of the buses and breakers, and give a certain amount of finish and completeness to the station. The cost of the cell structure is not great, and is only a small percentage of the total cost of the station.

For higher voltages the currents naturally become correspondingly less, minimizing the destructive effects of short circuits; and, on the other hand, the spacings required are greater, so that open work generally becomes preferable.

Various materials have been used for bus and oil circuit breaker compartments, namely, brick, concrete, soapstone and slate, and sometimes a combination of brick with one of the other materials. Brick compartments are the cheapest and, if properly made, give the best appearance. The use of common brick is, however, not recommended, because most of the walls are 4 inches thick and the sizes of the brick vary greatly, while, on the other hand, the bonds are so large that a neat job cannot generally be obtained. Inasmuch as the cost of laying the brick is about 75 per cent of the total cost, very little is added by substituting a face brick. With this type of construction, the compartment shelves are generally made of concrete or soapstone, from 2 to 3 inches thick, depending on the size of the compartment.

Concrete, although more costly, has gained in favor over brickwork, and therefore the majority of bus and switch compartments nowadays are built of concrete, especially for the larger stations. In some cases complete forms are made, usually of wood, and the whole compartment poured, giving a very substantial construction. More often, however, concrete slabs are used, set in cement.

The general dimensions of bus and switch compartments are determined by the minimum distance allowable between conductors and ground (see Table LII, page 653), the brick or concrete being considered as ground. The switching apparatus also governs the dimensions of the compartment, to a great extent, although even here it is generally a matter of ground distance in the apparatus. For mechanical reasons and accessibility, the distances are generally increased somewhat; this also guards against joints, clamps or bolts which act as spillways at times of abnormal voltage rises on the system. Low-voltage compartments, where relatively heavy copper is used, should have proportionally more liberal distances than those for equal capacities but of higher voltages, with connections of smaller size.

Removable doors are recommended for all openings of compartments, to prevent accidental contact with live parts, and in the case of oil circuit breakers, to prevent the scattering of oil should it be forced out of the oil vessels. Compartment doors should be made of light,

fireproof material and should be swung from the top to allow free movement in case of explosion in the compartment. Asbestos lumber with a light wood frame has proved to be the most satisfactory construction for compartment doors. Compartment doors should be considered as ground, that is, in respect to all live parts.

The arrangement of switch and bus structures varies considerably, depending not only on the system of connections, but also on the different designs of the circuit breakers. It is therefore impossible to give any definite recommendations that will meet all conditions. The station layouts (Figs. 97–104) shown in the section on "Arrangements of Apparatus," page 171, will serve to illustrate some typical arrangements which are self-explanatory.

In laying out the structure, attention should also be given to the current and potential transformers. The latter, with their fuses, require considerable space for higher voltages and have to be installed in certain positions. This refers especially to oil-cooled transformers and expulsion fuses; if in the preliminary design these points are not taken into consideration, considerable difficulty may be encountered in finding suitable accommodation for them. When current and potential transformers are installed in separate compartments, holes should be left in the partition walls to accommodate conduits for the secondaries between phases, and, in case of potential transformers, porcelain bushings should be provided for the primaries.

For voltages above 15,000 the circuit breakers are, as a rule, of the top-connected tank construction and compartments are entirely omitted, especially for the higher voltages. The conductors must necessarily be spaced farther apart and at a considerable distance from the floor, so as to be out of reach.

The busbars are an important part of the installation, carrying the whole energy of the plant in a confined space. The material is usually copper and the conductors may be either cylindrical rods or tubes or rectangular bars. The former are generally used for the high-tension buses and connections, but the latter are essential for lower voltages where large currents are to be carried, necessitating a larger cross-section. In such cases the bus is laminated, i.e., it consists of a number of bars arranged side by side with ventilating ducts between. This insures a large radiating surface, while at the same time this construction permits a tapering of the bus so as to utilize the material to the best advantage. Additional bars may also readily be added in case the capacity needs to be increased in the future.

The buses, as well as the connections to the oil circuit breakers, etc., should be so proportioned as not to attain an excessive temperature

rise under the maximum current which they are intended to carry. For direct-current work the features affecting the temperature rise are the size of the bar, the number of laminations, spacing of laminations, spacing between poles, whether the bars are run flat or on edge, and whether open or enclosed in compartments. For alternating-current work the heating depends also on the skin-effect and the inherent reactance of individual laminations and phases.

The permissible heating will depend on whether these busbars are simple uninterrupted carriers of electricity from one end to another, or whether connections are taken off the bus at certain points to circuit

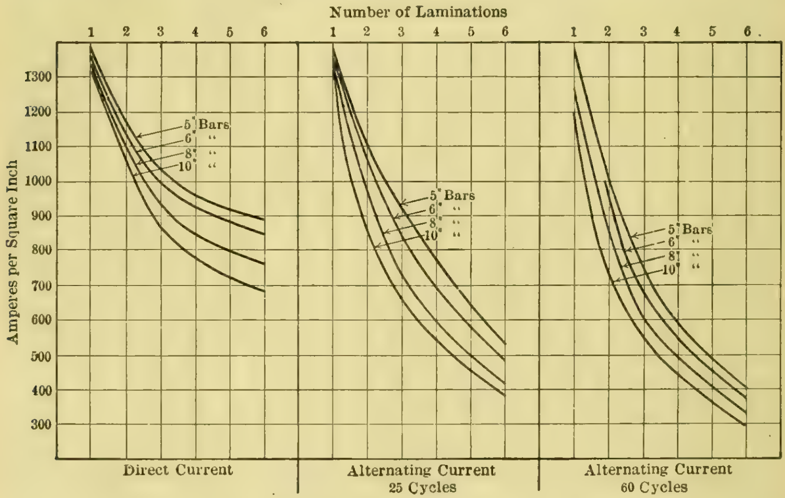


FIG. 385.—Permissible Amperes per Square Inch in Copper Connections.

Installed in Open Air on Edge.
¼″ Spacing between Laminations.
Laminations ¼″ thick.
8″ Spacing between phases.
30° C. Temperature Rise.

breakers, etc. In the latter case, the heating of the busbars or of the whole combination from bus to circuit breaker must be kept so low that the total temperature rise is below the temperature rise permitted for the breaker, which generally is 30° C. The connection bars should, therefore, in such cases be so proportioned as not to develop a temperature rise in excess of this value, and the temperature developed by the busbars should not be in excess of 35° to 40° C. above the ambient temperature.

The curves in Fig. 385, which have been derived from a large number of actual tests, show how the current density in amperes per square inch, based on a 30° C. rise, will vary in accordance with the number

and width of laminations. The bars are $\frac{1}{4}$ inch thick and run on edge, and the spacing between the laminations is also $\frac{1}{4}$ inch, and between the centers of the phases 8 inches.

The great variations in the density for the different conditions is apparent from the curves. An increase in the spacing between laminations from $\frac{1}{4}$ inch to $\frac{1}{2}$ inch will naturally increase the ventilation, and thereby the permissible current which can be carried at 30° C. rise, at least on direct current. For several laminations, run flat, that is, with their width parallel to the floor, the heating will be at least 25 per cent greater than when the bars are run on edge. Furthermore, consideration must be given to the fact that the ventilation of buses in compartments is not as good as in the open, and for this reason it will generally be advisable to limit the temperature rise for such conditions to a figure somewhat below the permissible temperature rise of buses in the open.

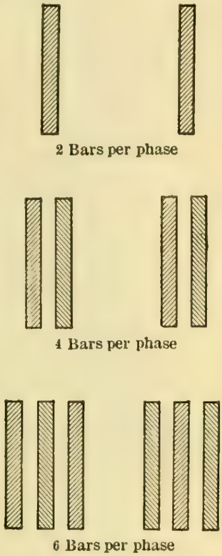


FIG. 386.—Method of Pairing Bus-bars to Reduce Skin Effect.

Skin-effect can best be taken care of by arranging the busbars so as to simulate a cylinder or tube; this is done by running the laminations as much as possible in pairs, as shown in Fig. 386. The distance between the pairs should then be as great as the space of the busbar compartments will permit.

With the bars run flat in the compartments, the connections can, as a rule, be made easier, but, as previously stated, the ventilation becomes poorer than if run on edge. On the other hand, installing them on edge gives a more substantial construction in that it increases their strength and ability to withstand short-circuit stresses.

With alternating current busbars run flat, the reactance of the laminations in the outside phases varies quite considerably, this effect being the more noticeable the less the distance between phase centers. The effect of this difference of the inductive reactance in the bars, due to the different distances between the middle phase and the individual laminations, will cause the lamination nearest the middle phase to develop the least reactance, and the lamination farthest away from the middle phase to develop the highest reactance. Therefore, the lamination nearest the middle phase will carry the highest current and the bar farthest away from the middle phase the lowest current. If the busbars are placed on edge this difference of inductive reactance in the

laminations disappears, and the only effects to be looked out for on A.C. busbars is then the matter of ventilation and skin-effect.

Both the buses and the connections should be securely supported and the insulators should be bolted or clamped to the pipe supports, walls, or slabs and not cemented, since this construction causes considerable inconvenience when it becomes necessary to exchange an insulator. Several different lines of busbar supports are now on the market, one representative type being illustrated in Fig. 387. The bus is shown mounted on edge, but by modifying the top cap it can also be laid flat.

Fig. 387.—Bus Insulator; Bus on Edge.

In designing the bus-structure in large stations, it is important to carefully consider the mechanical forces to which the conductors and buses may be subjected under short-circuit conditions. With currents thus flowing in two adjacent conductors, forces of attraction or repulsion are produced, depending on whether the currents are flowing in the same or opposite directions. In either case the instantaneous value of this force may be calculated from the following formula:

$$F=\frac{5.4\times I_1\times I_2\times 10^{-7}}{d}\text{ pounds per foot run;}$$

where I_1 and I_2 are the instantaneous values of the currents, and d the spacing between the conductors, in inches. With the comparatively large value of d which is used in power station work, the modifying factors due to proportions of the conductor width and height may be neglected.

In a three-phase circuit, the maximum forces are those occurring during a single-phase short circuit between phases, and the preceding formula applies; at this time $I_1=I_2$ and as they are in opposite directions the force exerted between bars is that of repulsion.

The value F multiplied by the distance in feet, L, between supports, gives the total force exerted on each insulator post.

While the busbars themselves have a certain amount of flexibility, the porcelain supports may be considered to have practically none. To be entirely safe, therefore, in the estimation of the possible stresses, it is customary to base the calculations on the maximum peak value of current corresponding to a totally displaced wave.

In stations of large capacity, precautions should therefore be taken to support the buses and their connections very securely. To meet such conditions, an insulator (Fig. 388) has been developed. It consists of two porcelain insulators, fitted loosely into the horizontal compartment barriers, as shown. Two alloy clamps of similar design, held apart by four brass pillars fitting loosely into holes in the clamps, form the support for the bars. The top clamp has a threaded stud extending into a hollow in the top insulator. By tightening the nut on this stud against the top insulator, the whole support is held firmly in place. By loosening this nut to the limit of its travel against the top clamp, it is possible to lift the top clamp for the reception of new laminations of bus or to remove the top insulator, there being just enough play to permit it to clear the top stud. Subsequently the remaining parts of the support can be easily removed for repair or inspection. The individual laminations of the bus are separated by fillers, and the number of laminations can be varied at will by using pillars of the proper length.

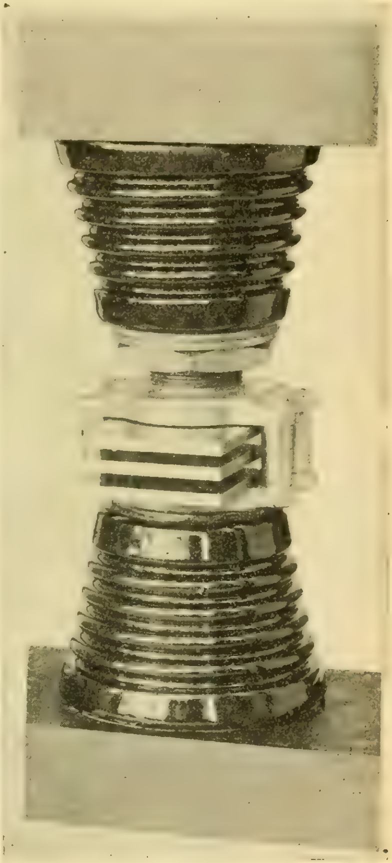


Fig. 388.—Bus-bar Support for Large Capacities in Compartments.

Figure 389 illustrates another type of heavy duty bus support of a bracket type.

The bus supports should be located near openings in the compartments, so as to be accessible for cleaning and inspection (Fig. 390).

This also refers to all the clamped joints between the buses and the connections.

In order to entirely exclude the possibility of interphase short circuits and their destructive effects, where large amounts of power are concentrated, some of the larger central station companies have adopted a new and novel bus-structure design. This consists in separating each phase of the three-phase circuits and the corresponding switching equipment by fireproof walls. The different phases may

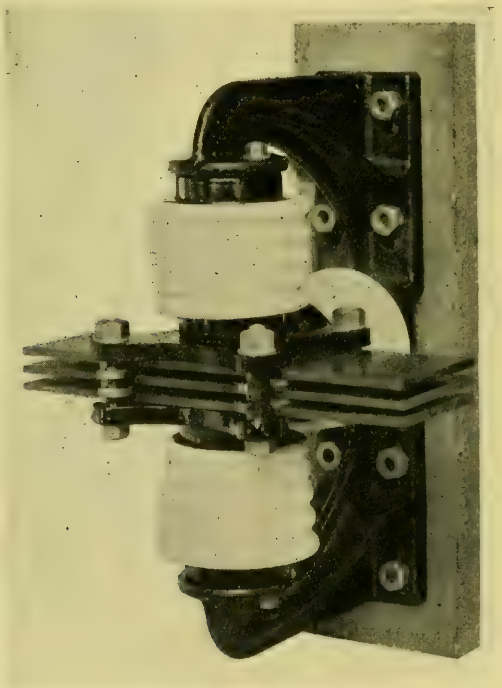


Fig. 389.—Heavy Duty Bus-bar Support of Bracket Type.

thus be installed in different rooms, either above one another or side by side, depending on the station layout. This scheme, of course, has necessitated an entirely new development of oil circuit breakers adapted for the purpose, so that the post of each phase of the oil circuit breaker may be operated simultaneously from a single operating mechanism. While this system has so far only been attempted with steam-turbo generating stations where the respective short-circuit currents are much larger than with hydro-electric stations, there is

no reason why it should not be equally well adapted for hydro-electric plants of very large capacity.

For very high voltages, the buses generally consist of round copper rods or tubing, the sizes given in Table LVI, page 662, being quite common. These buses are generally supported from the roof trusses by suspension insulators, and the connections on post-type insulators mounted on the walls (Fig. 391).

For long buses, provision must also be made for expansion and

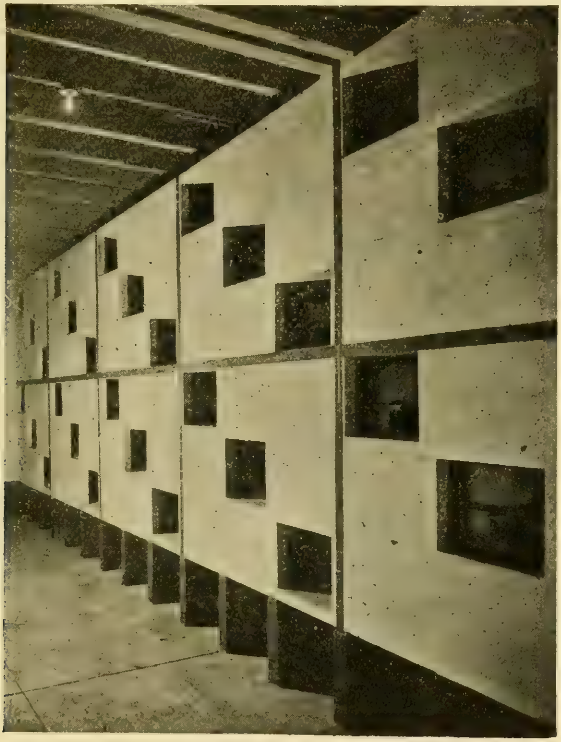


FIG. 390.—Low-tension Bus Compartments.

contraction due to temperature changes. The diagram in Fig. 392 gives the linear expansion of copper buses, the values being based on an installation temperature of 25° C. = 75° F. The actual expansion over any temperature range on the chart is the algebraic sum of the expansion values shown for the temperature limiting range. The chart has been corrected for variations in the coefficient, and the actual temperatures should, therefore, be used.

The problem of bringing a high-tension wire out of a building is

somewhat like that of bringing one out of a switch or transformer. The wire is brought out of the building through either the roof or the wall. No fixed rule can be made in this respect, since the method depends on the particular layout, arrangement of busbars, disconnecting switches, and lightning arresters. Weather conditions are also an influencing factor, and, where an abundance of snow is expected, wall

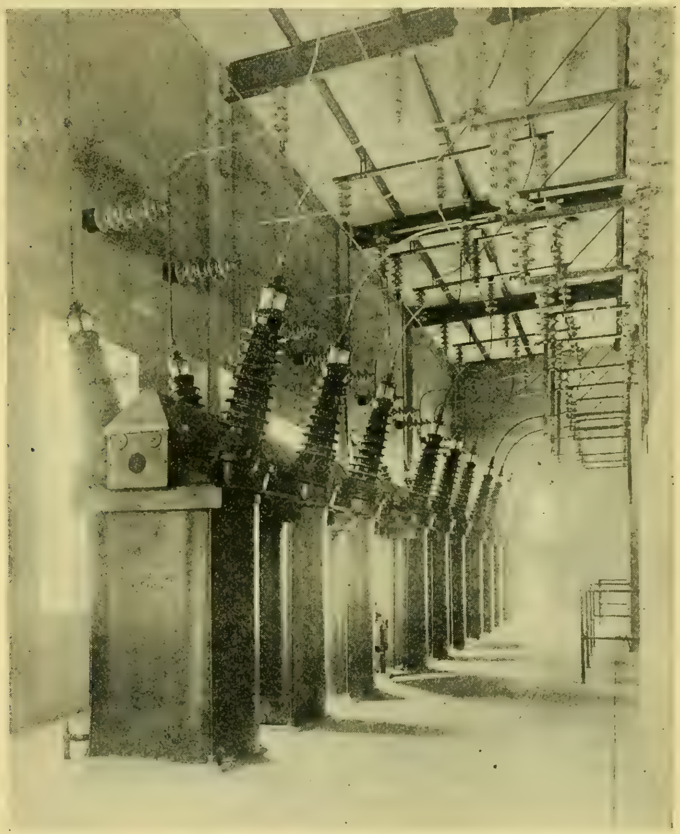


FIG. 391.—High-voltage Oil-circuit Breakers and Bus Structure.

entrances are usually preferable to roof entrances. Protecting hoods are also generally provided with wall entrances. Figures 393 and 394 show two typical designs of line entrances. Similar bushings are also used for high-voltage wall entrances.

Disconnecting Switches. In all high-tension circuits it is customary to install knife-type disconnecting switches for isolating oil circuit breakers, feeders, etc., and for making various connections that do not

have to be opened under load. For voltages of 3500 or less, these disconnecting switches are mounted directly on a base of marble or similar material, while for higher voltages, insulators of various kinds mounted on steel bases are used to support the switch jaws. Up to 25,000 volts, these disconnecting switches are made for either front connection or rear connection or both. For higher voltages they are

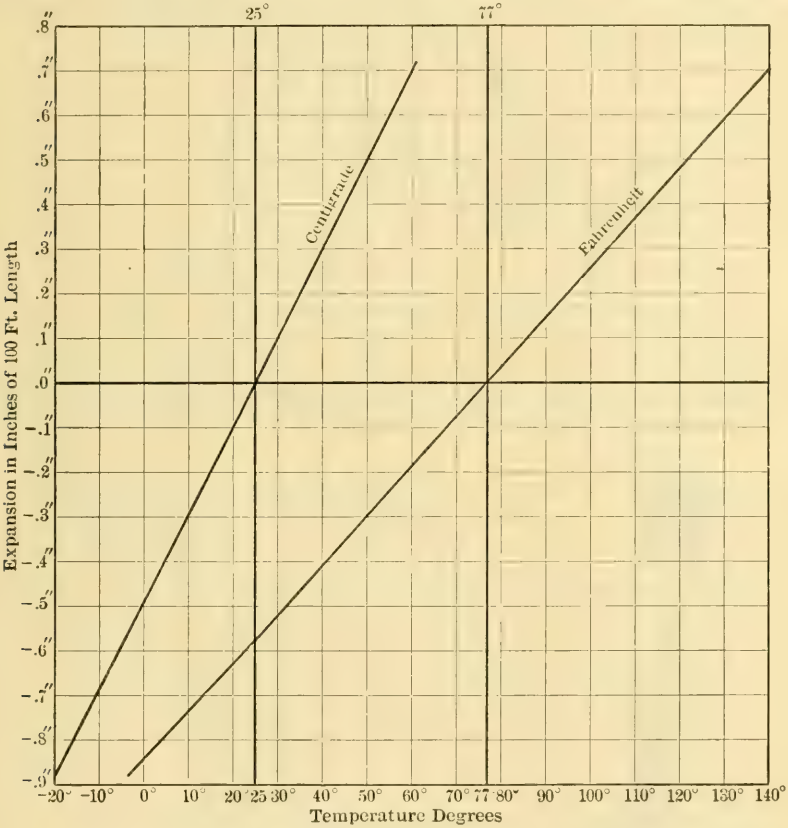


FIG. 392.—Linear Expansion of Copper Bus-bars.[1]

invariably made for front connection only, and in order to insure rigidity and prevent oscillations where the blade becomes very long, as for switches of the higher voltages, the blades may be of a truss design (Fig. 395), to prevent any tendency of a long blade to oscillate. Similarly, up to about 200 amperes, the switches are generally of single blade construction, while above this capacity multiple blades are used.

[1] By courtesy of General Devices and Fittings Company.

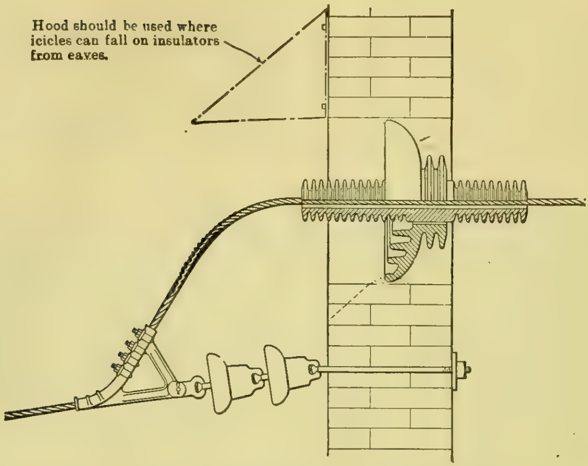


FIG. 393.—Typical Wall Entrance for Moderate Voltage.

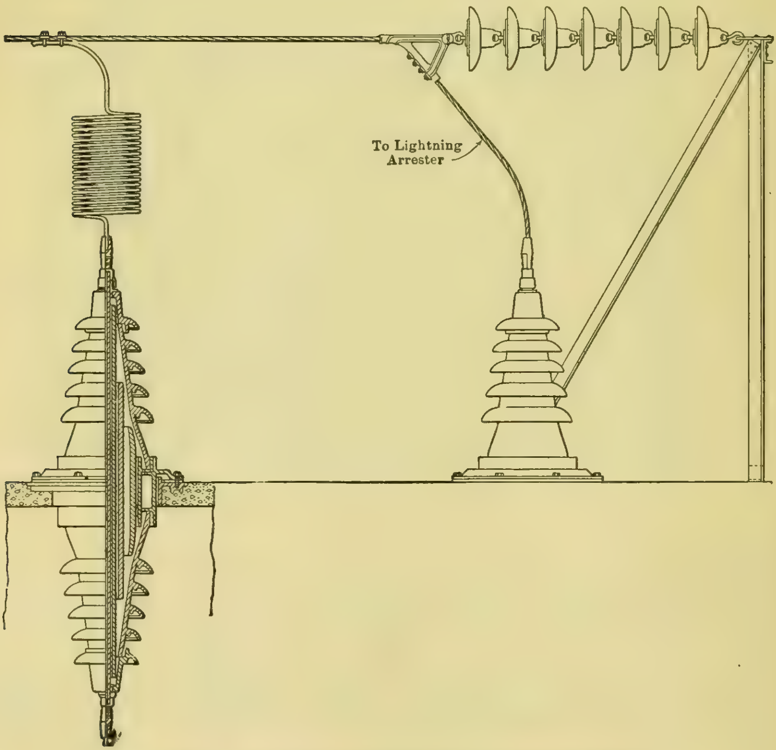


FIG. 394.—Typical Roof Entrance for High Voltage.

Disconnecting switches are usually operated by means of an insulating rod or switch hook, which is made of selected material especially treated for the purpose and capable of safely withstanding the operating voltage. For medium voltages, holes are provided in the ends of the switch blades for the insertion of the hook; but for higher voltages where the length of the handle may be 15 feet or more, it becomes difficult to insert the hook in the hole in the switch blade, and in such cases, hooks are provided on the blades, to engage with the operating hook when it is desired to open or close the switch.

In many instances, low and moderate voltage disconnecting switches, even for indoor service, are so arranged that the three poles can be operated simultaneously. In this case a permanent operating handle is provided for each set of switches. Interlocks may even be provided to prevent disconnecting switches from being opened or closed while the oil circuit breakers are closed. In some of the very largest central stations, the disconnecting switches are arranged to be operated from the oil circuit breaker mechanism, to close before the breaker closes and open shortly after the breaker opens. When so arranged, they may also be adapted to manual operation, and when manually operated they can be thrown to a third position for grounding the oil circuit breaker.

Safety catches are recommended and should be used whenever disconnecting switches are so mounted that the blades in closed position are horizontal or open downward. Under abnormal short-circuit conditions, disconnecting switches are also liable to be accidentally forced open, by the repulsion between the flux set up by the current in the blade and that produced in the parallel connections to the switch. The following table gives the maximum short-circuit current which the switches will carry without safety catches and not be forced open. Above these values, safety catches should always be used.

Rated Capacity of Switch in Amperes.	Maximum Current which Switches May Carry without Safety Catches.	Rated Capacity of Switch in Amperes.	Maximum Current which Switches May Carry without Safety Catches.
300	10,000	3,000	32,000
400	11,500	4,000	37,500
600	15,000	5,000	43,000
800	16,500	6,000	46,000
1200	20,000	8,000	53,000
1500	23,000	10,000	59,000
2000	26,500		

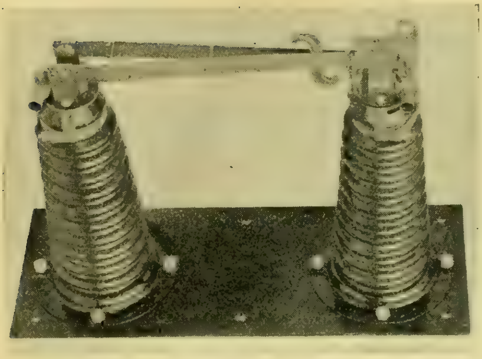


FIG. 395.—Single-pole, Single-throw High Voltage Indoor Disconnecting Switch with Combination Safety Catch and Opening Device.

Figure 395 shows a disconnecting switch equipped with a combination safety catch and opening device. It has an eye at one end of the lever for the hook, and a wedge at the other end which releases the catch. This device thus permits the release of the catch and the opening of the switch with one operation of the switch hook.

With the ordinary high-voltage, knife-blade, disconnecting switch, operated by a hook on the end of a long rod, a space must be left for the operator, directly below the switch and perpendicular to its base. The amount of space required will depend both upon the length of the blade and of the rod used to open and close it. In a few installations where the space is very restricted, a disconnecting switch, such as is shown in Fig. 396, has been used. It is operated from directly below by a disconnecting switch hook. It is thus possible to save the space that the operator would otherwise need to use the switch hook at the considerable angle required. The insulators, insulator caps, and terminals are standard. The blade is a copper rod with a cast eye fastened on one end and a readily renewable solid brass contact tip on the other. The stationary contacts are the same as those used on H-type oil circuit breakers.

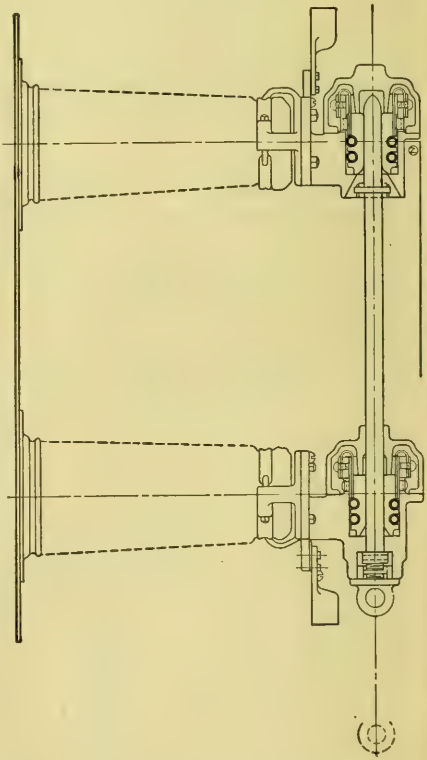


FIG. 396.—Special Disconnecting Switch for Restricted Quarters.

When the switch is opened, a flange near the tip of the blade prevents the blade from dropping below the upper part of the lower stationary contact. A wide flare on the lower end of the upper contact leads the blade into place when the switch is being closed. After the

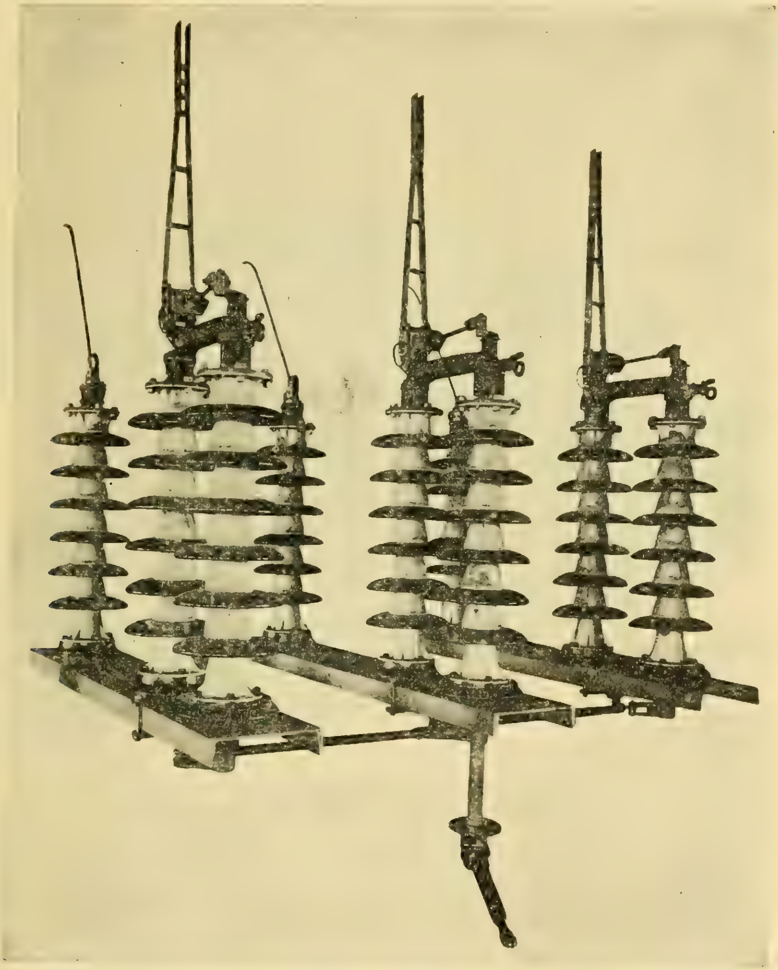


FIG. 397.—110,000-volt, Three-pole, Single-throw, Disconnecting Switch.

blade is closed, a slight turn to the right or left, by the operating rod, locks the blade in position and prevents it from opening except when desired.

The type of disconnecting switch shown in Fig. 397 is intended for use on heavy outdoor service, and can be built up to any operating

voltage in use. All three poles are operated simultaneously by a lever or handle, which can be located at any height from the ground, and locked in either open or closed position. It may also be arranged for motor operation from a remote point.

As seen from the illustration, the switch is provided with horn-type arc deflectors on the stationary contact, by means of which it is permissible to rupture the exciting current of small transformer banks. The shape and location of the horn, in conjunction with the upward movement of the switch blade, definitely confines the arc to the horn and blade, and quickly ruptures it without short-circuiting the line or involving adjacent apparatus. Up to and including 120,000 volts, the switch is generally of single-break type. This is also the case for higher voltages, while if intended for rupturing transformer exciting

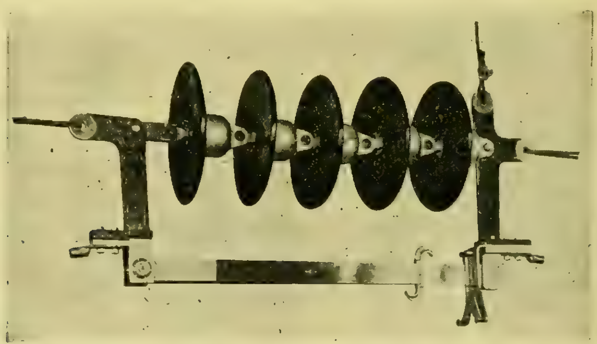


Fig. 398.—90,000-volt Outdoor Disconnecting Switch with Strain Insulators.

currents it is usually made double-break for these higher voltages. Such a switch merely consists of two single-break elements mounted back-to-back with a common operating column.

In operating the disconnecting switch, the blades move in a vertical plane, describing an arc of 90° to go to the full open position. When the switch opens an arc, the arc is drawn upward on the arc deflector and the end of the switch blade. The construction of the switch blade is such that any snow or ice that has collected on stationary contact or contact parts of the switch is readily removed by the opening or closing of the switch. The operating mechanism can be thoroughly grounded to prevent any danger to the operator.

A suspension-type switch, for mounting directly in a transmission line at the point of support of a tower, is shown in Fig. 398. The blades are suspended underneath a string of strain insulators and open downward. The end of the switch, with its T-shaped casting, is supported

from the suspension insulators, and the L-shaped casting on the opposite end is connected directly to the span and is dependent on this to support it in an approximately horizontal position. The blade guide serves also as a safety catch to hold the blade closed.

Signal Systems. In large power stations it becomes essential to provide some means of communication between the switchboard operator and the machine attendants, and different systems of illuminated dials, bells or whistles are used. It is important that this apparatus should be located in a position most convenient to the operators, so as to save time and avoid possible errors at critical

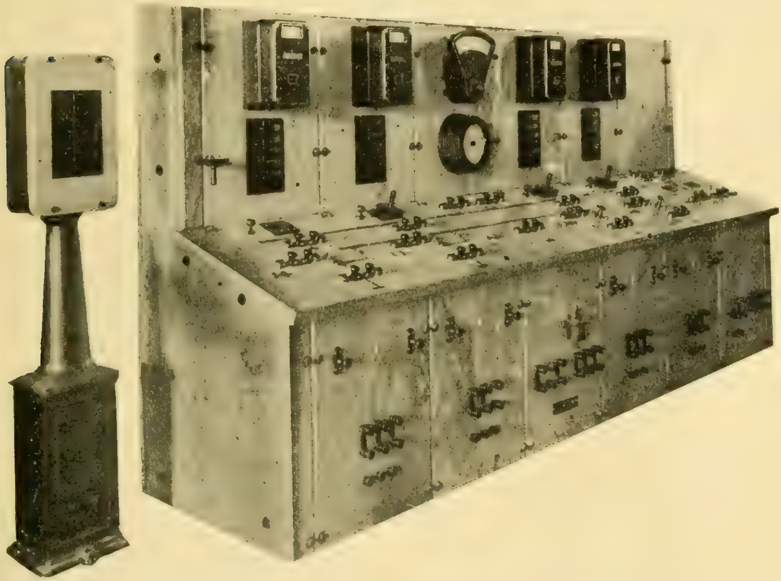


FIG. 399.—Individual Push-button Signal Equipment with Stand for One Machine.

moments. Direct visual signals between these persons are practically impossible, without a moving or turning by the switchboard operator from his position before the instrument and control apparatus. This should not be expected of him, as it would mean relocating himself with reference to the switchboard equipment for every signal received or sent.

In stations of moderate size it may be sufficient to install one common large illuminated sign which is visible from any place in the station. This sign contains the unit numbers and the most important signals, such as "start," "stop," "stand-by," etc., and is controlled from the switchboard, a whistle being used for calling the operator's attention

to the signals. Sometimes provision is also made for answering or returning the signals to the switchboard.

A very satisfactory and generally used signal system is the individual push-button equipment, shown in Fig. 399. It consists of an individual stand for each machine unit, with the signals mounted thereon, as shown. Similar signal equipments are also provided on the respective machine panels on the benchboard, the two corresponding equipments being connected together electrically. The signals consist of colored glass windows with white letters illuminated by small lamps behind. Opposite each signal is a three-way push-button switch, and a gong is installed near each machine and also at the switchboard. Pushing a button, for example, at the switchboard rings the gong at the machine to which the signal is sent, simultaneously illuminating the particular signal which was sent at both places. The gong keeps on ringing and the signal remains illuminated until the machine operator acknowledges the signal by pressing the corresponding button on his equipment. The connection diagram for a small equipment of this type is shown in Fig. 400.

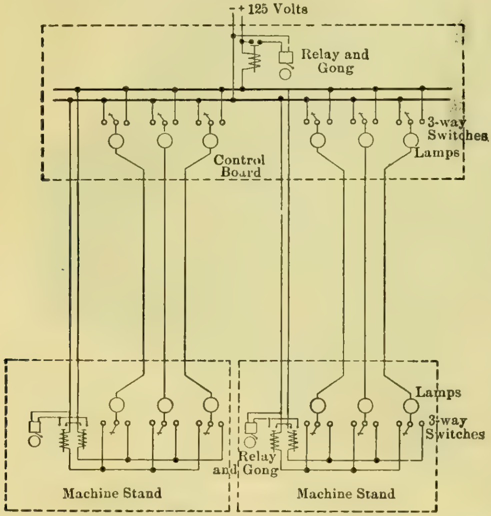


FIG. 400.—Connection Diagram of Two Signal Equipments with Three Signals.

It is, of course, not necessary to install the signals near the machines on pedestals. They are often located on the nearby wall where they can easily be seen, and occasionally various colored lamps are installed at the side of the respective signals so that they can be read more quickly and distinctly from a distance. One company, for example, uses a blue light beside the "stand-by" signal, a red for the "fast," a green for the "slow" and white for all the others.

What the signals should read depends, of course, to some extent on the local operating conditions. The following are, however, very common: "Stand-by," "start," "fast," "slow," "stop," and "O.K." These are used in the power-house of the Pennsylvania Water and Power Company, their meaning being as follows:

"*Stand-by*": Stand near governor and await further orders. Correct any apparent governor trouble. Trouble impending. The "Stand-by" signal is to be used during the cutting out of units, tests, lightning storm, or other expected troubles.

"*Start*": Start unit at once on hand control.

"*Start Fast*": (Combination signal). Start unit as quickly as possible.

"*Fast*": If unit is not on the bus, increase speed. If unit is on the bus, increase gate opening gradually. If the signal is flickered, increase rapidly.

"*Stop*": Shut down unit at once.

"*O.K.*": Unit on bus. Engage governor-control motor gear. Conditions normal. Further attention not needed. Cancels "Start" or "Fast" signal. The "O.K." signal is also used when unit has come to rest and field has been taken off.

The whistle used in this power station is electrically controlled from the switchboard and is operated by compressed air at 300 pounds pressure. It is located at one end of the power-house and is loud enough to be heard over the noise of the machinery in all parts of the building, and can be heard outside the building for quite a distance. It is used principally for calling persons connected with the operation, the code being as follows:

Attention to signals —

Assistant operator —— ——

Machine man — —

Lightning storm on ——— — —

"On hearing this signal a special arc extinguisher observer will report to operator."

Hydraulic floorman —— —— ——

Hold frequency —— —— —— ——

This is an emergency signal to be used in case the station is swamped or running away. "If the station is swamped, force all machines to full gate opening; if running away, close all hand-control machines until frequency returns to normal. If governor system has failed, governor machines must be changed over to hand-control and regulated until frequency returns to normal. Pumpman must make every effort to hold pressure on governor and hand-control systems, starting pumps and taking any other necessary steps. Extra men, unless otherwise detailed, to report to floorman on governor floor."

Emergency stand by ————————————————

"Serious general emergency existing or impending. All attendants stand by. Extra men report to floorman or operator, unless otherwise

detailed. Chief and assistant chief operators proceed to bench board, maintenance men report to chief operator."

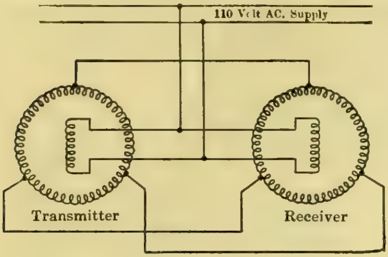


FIG. 401.—Diagram of Connections of Position Indicator.

There is another emergency whistle located on the roof of the building, for the purpose of calling assistance during operating emergencies and for calling the operating heads and company physician in case they can not be located by telephone. This whistle can be heard a distance of five or six miles.

A very reliable and accurate method of communication is obtained by the Selsyn position-indicating system. This system was first used at the Keokuk plant of the Mississippi River Power Company, to send and receive signals between the switchboard and the generator room, neither of which is visible from the other.

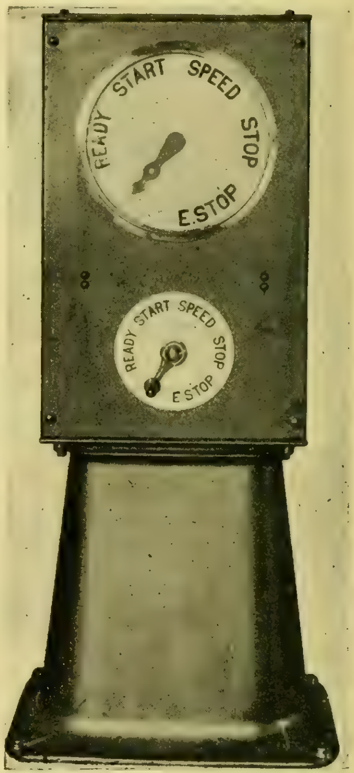


FIG. 402.—Signal Equipment at Mississippi River Power Company. Generator Room Pedestal.

Fundamentally, the system consists of a special electric transmitting generator electrically connected to a similar receiving motor, as shown in Fig. 401, so that every angular movement of the transmitting generator motor is duplicated instantly by a similar movement of the rotor of the indicating motor. The generator rotor is thus operated mechanically by a handle, and a pointer attached to it moves over a circular dial, on the outer edge of which are printed the signals or instructions to be given. The shaft of the motor is also fitted with a pointer which moves over a similar dial. Thus, when the transmitter pointer is turned to any point, the indicator pointer moves in unison to a similar point on its dial and gives the instruction or the signal desired. For answering signals or instructions, a duplicate set is used, arranged

in the reverse order. Figure 402 thus shows a pedestal equipment for locating near the respective generators, while in the switchroom the indicators are generally mounted on the generator switchboard panels. The smaller dial with the handle at the bottom of the pedestal panel is the transmitting dial, and the upper the receiving dial.

The method of signaling is as follows: When the switchboard operator desires to send a signal he turns the handle of the transmitter until its dial indicates the signal he wishes to send. This signal will be indicated on the dial of the receiver in the generator room. He then pushes the button on the right of the handle. This lights a lamp on the generator (Fig. 3) and blows a whistle in the generator room to attract the attention of the man in charge of the particular machine. As soon as the attendant has read the signal on his receiver, he will turn the handle of the transmitter on the pedestal to the same signal. He will then push the button at the right of the handle, which will extinguish the lamp and cut out the whistle. Next he will push the button at the left of the handle, which operation will light a lamp in the switchboard room and also ring a signal bell indicating to the switchboard man that the generator attendant has received the signal and also just what signal he received. The switchboard operator, after having seen this returned signal, will push the button at the left of the transmitter handle, which will extinguish the lamp and cut out the signal bell. This completes the cycle of sending and receiving a signal.

The signal system in any important station is always supplemented by a multiple-station intercommunicating telephone system. This is used when special orders or instructions are to be given.

Oil Circuit Breaker Batteries. The operation of remote-control oil circuit breakers, field switches, field rheostats, signal lights, etc., necessitates an absolutely reliable source of energy, which should be entirely independent of the regular distribution circuits and held in reserve exclusively for this purpose.

It is usual, therefore, to install a motor-generator set consisting of an induction motor driven by power from the A.C. circuit, direct connected to a direct-current generator. In order, however, to insure continuity of service in case of an interruption in the supply of current from this machine, whether due to failure of the power supply on the A.C. circuit or to some derangement in the machine itself, it is standard practice to install a storage battery, which is normally kept floating across the terminals of the direct-current machine. This motor generator is kept running continuously, except for the brief periods of time during which it may have to be shut down for inspection or repairs, and under normal conditions it carries the steady load due to the signal

lamps, and supplies a small amount of charging current to the battery in order to keep it fully charged at all times and ready for service. This direct-current machine is of the shunt-wound type having a decidedly drooping characteristic, so that when a heavy demand occurs, due to the opening or closing of oil switches, etc., the load is divided between the machine and the battery, and the machine itself is thus protected against excessive momentary overload. It should be designed for the maximum charging voltage of the battery, which, for lead batteries, may rise to about 2.7 volts per cell. The ampere capacity of the generator should be equal to the normal charging rate of the battery plus the current required for the signal lamps, about $\frac{1}{10}$ ampere being needed for each such lamp at 125 volts.

It will be noted from the above that under ordinary conditions of operation the battery does very little work, and the maximum demand upon it occurs only when it is necessary to open or close a number of switches simultaneously.

The normal voltage of control circuits is mostly around 125 volts, although for large stations 250 volts may be preferable. In the former case the number of cells is usually fixed at 60, and for this number a floating voltage of about 125 volts is suitable.

The ampere capacity of the battery is determined by ascertaining the maximum possible demand due to the simultaneous operation of as many of the remote-control devices as are liable to be operated at once, and selecting a battery of sufficient size to supply this current for the period of time necessary, without dropping in voltage below a certain permissible minimum. Thus, in order to provide an ample margin of safety for the remote-control apparatus, a minimum final voltage of 105 (1.75 per cell) is usually fixed for a 125-volt battery, when carrying its maximum load. One minute has been taken as the time duration of the maximum demand. A properly designed lead storage battery, equipped with low-resistance intercell connections and provided with conductors of ample capacity for connecting to the switchboard, may be discharged at $2\frac{1}{2}$ times the one-hour rate (10 times the eight-hour rate) for a period of one minute without dropping below the limiting voltage of 1.75 per cell above mentioned. Oil circuit breaker batteries are frequently, therefore, designed to work at $2\frac{1}{2}$ times the one-hour rate when the maximum possible load is to be carried with the motor generator set shut down.

In order to determine the maximum possible load, it is usual to figure that not more than one or two remote-control switches will be closed at one time, and not more than one-half of the total number of automatic switches will be tripped simultaneously. When more than

twenty oil circuit breakers are installed, it is considered safe to figure on not more than one-third of the total number of automatic breakers being tripped at the same time. The duration of any single switching operation is but a fraction of a minute, and a battery subjected to intermittent discharges at high rates recuperates rapidly during the intervals of rest, so that a battery figured as above will easily handle as many successive operations as are liable to be required. The current required for the operation of oil circuit breakers, etc., varies with the size and make, and should be obtained from the respective manufacturers.

In some cases an emergency station lighting circuit may be arranged for connection to the oil circuit breaker battery in case of complete interruption of other sources of light. To provide for this, a battery of greater ampere-hour capacity may be required than that determined by the oil switch service alone. The required additional capacity should be calculated on the basis of one- or three-hour emergency service and should be added to the capacity needed for the operation of the circuit breakers. The three-hour discharge rate of a lead cell is twice that of the eight-hour discharge rate, and the one-hour rate is four times that of the eight-hour rate.

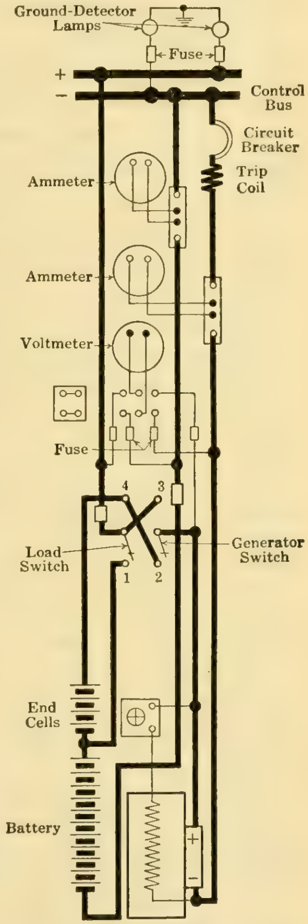


FIG. 403.—Diagram of Connections for Oil Circuit Breaker Storage Battery.

A diagram of connections of this scheme is shown in Fig. 403. For normal operation the generator switch and the load switch should be in positions 3 and 4 respectively, floating the battery on the motor-generator. For charging the battery, the load switch should first be thrown to position 1, thus connecting the control circuit across the 50 cells and preventing it from being subjected to the high charging voltage. The generator switch is thereafter thrown over to position 2, and the voltage of the generator, which is still connected across the 60 cells, is raised until the desired charging current is obtained.

For the sake of illustrating the operation, assume that the generator is now delivering 30 amperes, and that the load of the control lights is, say, 5 amperes. The full current of 30 amperes will, therefore, pass through the end-cells, but only 25 amperes (30 − 5) through the main cells, for which reason the former will be fully charged before the latter. During the latter part of the charge, the generator switch should, therefore, be thrown over from position 2 to position 3, leaving the load switch in position 1, and the generator voltage lowered. It is then evident that, of the full generator current of 30 amperes, 25 amperes will now flow through the main cells, the remaining 5 amperes flowing directly to the control circuit to supply the load. No current will flow through the end cells.

On completion of the charge the load switch is thrown over to position 4, and the conditions will be identical with those existing at the beginning, with the battery floating across the generator.

An overload circuit breaker is provided in the negative lead from the generator. In some cases a reverse-current trip has been provided for this circuit breaker; but this is usually omitted, owing to the fact that a momentary variation of frequency on the system might lower the speed of the motor-generator set and reverse the current, thus tripping the circuit breaker unnecessarily. A momentary reversal of current through the generator would usually be quite harmless.

In the battery leads fuses are inserted rather than circuit breakers, as it is not desired to have the battery circuit open except under extreme conditions, such as short circuit in the control system.

When the battery is kept continually floating at practically constant voltage across the D.C. operating bus, and another source of current, such as a motor-generator set, is provided to supply the steady load of signal lamps, etc., so that the battery work is limited to occasional momentary discharges when the oil switches are operated or to such sustained discharges as may be called for in case the normal source of current should fail—in other words, where the conditions call for strictly emergency stand-by service from the battery—the pasted type of battery in glass jars, or a similar type, is recommended, this being the same type that is now generally used for stand-by service in the large central station lighting systems. Where a method of operation is adopted in which the battery is discharged continuously on the bus until nearly exhausted, and then recharged, thus involving repeated cycles of charge and discharge, a formed positive plate, like the Manchester type or its equivalent, is recommended, the pasted plate being only recommended for use on floating batteries at approxi-

mately constant voltage and discharging only under temporary emergency conditions.

Automatic Generating Stations. Several years of successful operation of a number of automatic and semi-automatic hydro-electric generating stations have now amply demonstrated the feasibility and economy of such stations. While, from a technical point of view, there seems to be no limit to the capacity of automatic stations, the greatest field appears to be for small and medium-sized installations, especially where such stations form an auxiliary to a larger system.

In a large, manually operated station, the cost of attendance becomes a small part of the total cost of the energy produced, and the saving effected by eliminating the operating force may not be justified, especially in plants with complicated switching systems, where, as a rule, skilled operators are required. For small and medium-sized plants, however, economic success may often depend on the entire or partial elimination of the operating force, as the operating expenses are thus reduced to a minimum, without sacrificing reliability of operation. A periodic inspection by a line-patrol man, or any other qualified person, may be the only attendance required, or the services of a single watchman may be sufficient.

Existing manually operated installations can frequently be made automatic; but such a change requires careful study, and it is often found inadvisable merely to augment the manual installations with automatic features.

A distinction is commonly made between two classes of automatic generating stations, viz.:

I. Semi-automatic

(*a*) Remotely controlled, either governed or ungoverned. In the former case the generator unit is started from the main station by remote control of the governor control solenoid, and synchronized by throwing it on the line and applying the field excitation. Non-governed remote control stations are started and synchronized by a gate motor or a nozzle motor.

(*b*) Started manually, but provided with sufficient protective features so that it may operate unattended. This is the most economical way of controlling small generators, say under 100 kv.a.

II. Completely Automatic

These are generally governed, for which reason no synchronizing motor is needed, and the starting is accomplished

through a governor control solenoid. The synchronizing takes place in the same manner as for the semi-automatic station, although it is accomplished automatically through the governor action and the proper control sequence.

An automatic station may thus be defined as one that, at the indication of a master circuit, goes into operation by an automatic sequence, which thereupon maintains by automatic means the required character of service; that shuts down and clears itself automatically at the opposite indication of the master circuit, and protects itself while starting, running and shutting down.

Figure 404 shows a simplified wiring diagram of a semi-automatic remote-controlled synchronous generator station, in which the operator in the main station has complete control of the speed, and therefore of the load that the remote station will carry. The operator closes the control switch in one position, which causes the water-wheel gate to open, thus starting the generator. The field of the generator is connected to the armature of a direct-connected or belted exciter by the closing of the contactor in the main field circuit, and the generator builds up the voltage as the speed increases. The operator, with a synchronism indicator across the oil circuit breaker in the main station, adjusts the speed and synchronizes the generator as if it were a machine in the same plant. After the generator is synchronized, the load, which is under the operator's control, may be adjusted to any desired amount.

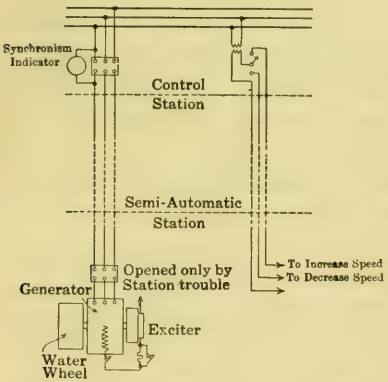


FIG. 404.—Simplified Wiring Diagram of Remote-controlled Semi-automatic Generating Station.

Synchronous generators are generally used with automatic stations and have thoroughly demonstrated their reliability even for this service. They are, in most cases, provided with amortisseur or squirrel-cage windings, to assist their pulling into step with as little disturbance to the rest of the system as possible.

Various schemes of complete automatic control equipments have been standardized. Such schemes may thus, for example, be arranged with a pre-determined field setting, or with an automatic voltage regulator. The installation may further involve one or more generators.

Figure 405 shows a wiring diagram of a typical scheme with predetermined field setting and Fig. 406 gives the nomenclature used therein. The station may be started by a master starting element No. 1, or directly by energizing the A.C. lines at the main station. Element No. 1 may be a float switch, a time switch, a lever switch located at any point, or any device to operate the master control-contactor No. 4. When this contactor closes it energizes and lifts the plunger of governor solenoid No. 65. This admits oil to a cyl-

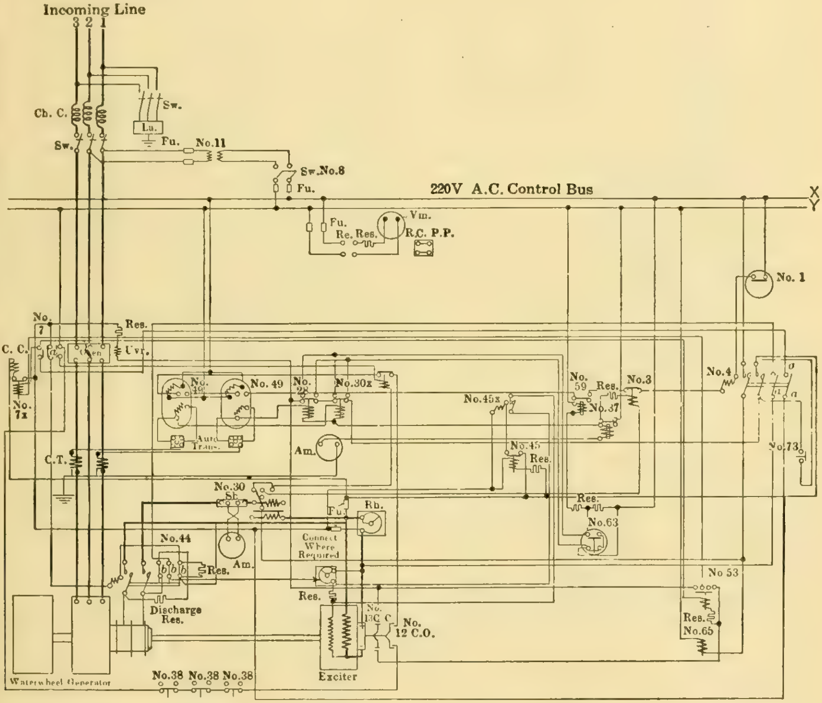


FIG. 405.—Wiring Diagram of Automatic Switching Equipment. Waterwheel Driven Synchronous Generator with Predetermined Field Setting.

inder causing the gates to open. When the generator has reached approximately 95 per cent of synchronous speed, the speed control switch No. 13 closes, and when the exciter voltage has built up to about 70 per cent normal the exciter relay No. 53 picks up and energizes the closing coil of the solenoid-operated oil circuit breaker from the exciter. When the oil circuit breaker closes, an auxiliary switch completes the coil circuit of field contactor No. 44; this contactor closes and connects the generator field to the exciter. The generator is now connected to

the system and will take load corresponding to the governor setting, or a load regulating device.

By modification of this control, two or more generators can be automatically started, synchronized and operated in parallel on a common bus.

To shut down the generator, the line may be disconnected at the generating station, which is equivalent to removing all the load from the generator. Underload relay No. 37 energizes, stopping relay No. 3, which causes the station to be shut down after a short time delay.

C.C.	Circuit Closing.
VM.	Voltmeter.
U.V.R.	Under Voltage Release, Self Resetting.
SW.	Switch.
SH.	Shunt.
RH.	Rheostat.
Res.	Resistor.
RE.	Receptacle.
P.P.	Potential Plug.
LA.	Lightning Arrester.
FU.	Fuse.
CT.	Current Transformer.
CO.	Circuit Opening.
CH.C.	Choke Coil.
CL.C.	Closing Coil.
b.	Auxiliary Switch, Closed when Main Switch is Open.
AM.	Ammeter.
a.	Auxiliary Switch, Open when Main Switch is Open.
73.	Limit Switch on Wheel Gate.
65.	Governor Solenoid.
63.	Oil Pressure Relay.
59.	Over-voltage Relay.
53.	Exciter Relay.
49.	A.C. Machine Temperature Relay.
45x.	Auxiliary Relay for No. 45.
45.	Exciter Over-voltage Relay.
44.	Synchronous Generator Field Contactor.
38.	Bearing Temperature Relay-hand Reset.
37.	Underload Relay.
30x.	Auxiliary Relay for No. 30—Hand Reset.
30.	A.C. Field Machine Relay.
28.	A.C.Overload Time Delay—Hand Reset.
13.	Synchronous Speed Control Switch.
12.	Speed Limit Switch.
11.	Control Power Transformer.
8.	Control Power Switch.
7x.	Auxiliary Relay for No. 7.
7.	Oil Circuit Breaker and Mechanism.
4.	Master Control Contactor.
3.	Time Delay Stopping Relay.
1.	Master Starting Element.

FIG. 406.—Nomenclature to Fig. 405.

The generator can also readily be shut down if the master starting element opens, through the action of a float, etc., or by opening control switch No. 8. All devices then return to their proper position for re-start.

Protection is provided against the following:

1. Severe overload on the generator. Relays No. 28 open their contacts and drop out contactor No. 4, causing the oil circuit breaker to open. As the No. 28 relays are hand reset, the station must be visited before the machine can be re-started. These relays are set high, however, so that they will not trip except in cases of excessive overloads.

2. Overheated machine windings. Machine thermal relays No. 49, connected to the current transformers, prevent the overheating of the machine windings in case of moderate continued overloads, or running on single or badly unbalanced phases. They have a thermal characteristic similar to that of the machine, and are calibrated to operate slightly ahead of the danger point. After the windings have cooled, service is resumed if the incoming line is energized.

3. Overheated bearings. Bearing thermal relays No. 38 are pro-

vided to protect the unit by opening contactor No. 4, should the bearings become overheated. These relays are hand reset and require the presence of an inspector to put the machine into service again. One No. 38 relay is provided for each bearing.

4. Overspeed. Speed limit switch No. 12 is provided to shut down the machine in case of overspeed. This switch automatically resets when the speed falls sufficiently, allowing the machine to re-start at approximately 85 per cent synchronous speed.

5. Failure of oil pressure. An oil pressure switch No. 63 is provided, which, in case the pressure of the oil operating the gate falls below a predetermined value, will short-circuit a section of resistance in the circuit of over-voltage relay No. 59. This opens No. 59, which in turn opens contactor No. 4 and shuts down the station. When the oil pressure becomes high enough for proper operation, relay No. 63 permits the machine to re-start, if the incoming lines are energized.

6. A.C. over-voltage. If the voltage becomes too high for safe operation, relay No. 59 will pick up and open contactor No. 4, shutting down the machine. When the voltage drops to a normal value (in case the station is tied-in with another system) No. 59 will reclose its contacts and permit the machine to re-start.

7. Loss of excitation. Relay No. 30 will drop and close its contacts. This will energize hand-reset relay No. 30x, which shuts down the station. The presence of an inspector is required before the machine may be re-started.

8. Momentary dip in voltage sufficient to drop out contactor No. 4. Limit switch No. 73 is closed and therefore completes the coil circuit of the under-voltage device on the oil circuit breaker. The gates will start to close; but if the voltage returns to normal before the exciter voltage falls too low, contactor No. 4 will pick up again and the machine will not be disconnected from the line.

Figure 407 shows a typical automatic hydro-electric station.

9. OVER-VOLTAGE PROTECTION

Classification of Over-voltages. High-voltage disturbances may be divided into two broad classes: first, that covering actual high voltages in which the excess voltage exists between the phase conductors or between the phase conductors and ground; second, that covering localized high voltages in which the excessive potential difference exists between two points along the same conductor. In these cases the " conductor " is supposed to include the line wires as well as the generator and transformer windings.

To the first class belong those disturbances which are caused by overspeeds, poor regulation and resonance, while the nature of disturbances caused by switching, arcing grounds, and lightning is such that they may belong to either class. Where the impulses or traveling waves set up are of comparatively low frequency and consequently of sloping wave front, the disturbance can, however, generally be classed with the former, and when of high frequency and steep wave front with the latter.

Excessive over-voltages are very apt to occur when water-wheel-driven generators run away, especially if they are provided with direct-connected exciters. Actual experience has thus demonstrated that under such conditions the generator and transmission voltages may reach three times their normal value, which, of course, subjects the apparatus to unreasonable strains. To guard against this, such apparatus is provided with automatic brake equipments, or high-voltage cut-out relays which automatically insert resistances in the exciter fields if the voltage exceeds a certain predetermined value.

In the design of modern long-distance transmission lines it is generally the regulation, or the variation in voltage which occurs when the load is thrown on or off, that is the governing factor, rather than the energy loss. Not only may the voltage drop under load be quite large, especially when the load has a low power factor, but with the high-transmission voltages now in use the capacity effect of the lines becomes very high, which in turn may result in a considerable voltage rise at the sub-station at light loads. This is now one of the chief arguments against isolated delta connection for long-distance high-tension lines. It was formerly claimed that such a system could be temporarily operated with one line grounded. Recent experiences on large systems, however, indicate that this is not feasible, as in the event of a ground the charging current, which is a function of the voltage from wire to neutral, will be increased because the natural is shifted from the center of the delta to one corner. This increase will be about 73 per cent and will, of course, in turn cause an additional voltage rise at no load, which is not permissible.

The voltage rise caused by the charging current in a long line may cause a breakdown of the air nearest the line conductor, and cause corona, which may seriously increase the transmission losses. It may also unduly strain other insulations on the system and affect the operation of the lightning arresters, the normal voltage range of which should be kept within reasonable limits for satisfactory operation. On the other hand, it is well known that the operation of motors is affected by voltage variations and that the life of lamps is seriously reduced if the

voltage is too high, not to speak of the unpleasantness of a variation in the intensity of the illumination, which of course accompanies a fluctuation in the voltage.

It is imperative, therefore, that the regulation of a modern system be kept within certain permissible limits, and with high-voltage systems this is most readily accomplished by installing synchronous condensers with automatic voltage regulators in the sub-station. As previously stated, the large capacity currents of long-distance lines cause a rise of voltage from the generator to receiver at light load, while at full load the lagging current taken by the load will cause a drop

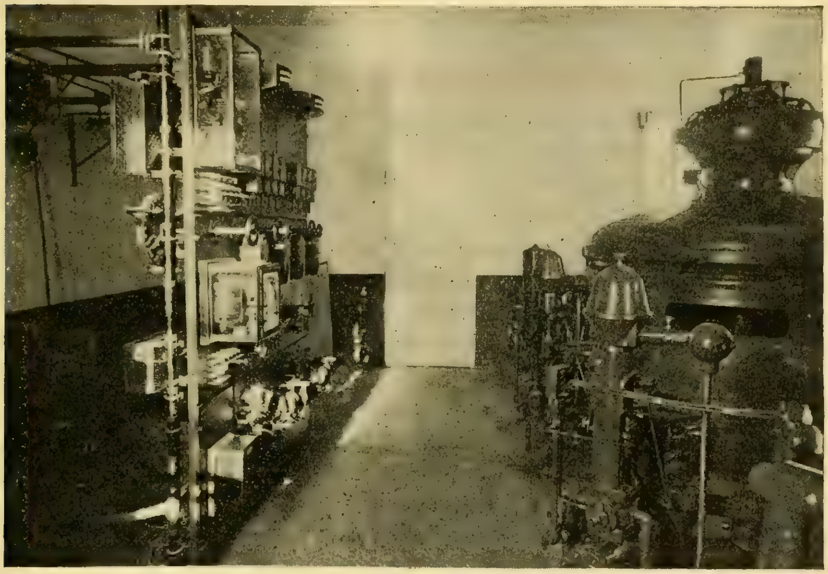


Fig. 407.—Typical Automatic Generating Station.

of voltage from generator to receiver. It is evident, therefore, that the voltage may be kept constant or within certain limits, at the receiving end, if a synchronous condenser is installed there, and its field adjusted so as to make it take a lagging current at no load and a leading current at full load; in the first case to offset the effect of the line capacity and in the second to offset the surplus lagging load current.

Resonance must also be guarded against, as it can give rise to large currents which may open the circuit-protecting devices and interrupt the service, or the potential may be raised to a value at which the installation of the system is broken down. In an electric circuit the inductive reactance and the capacity reactance oppose each other. If of equal

value they neutralize each other, in which case the resistance of the circuit limits the value of the current. This may, therefore, reach very high values, and when passing through the inductance and capacity the voltage at these would in turn be very high.

To illustrate this further: assume a circuit having a resistance of, say, 50 ohms and a capacity reactance of 1000 ohms; then the total impedance would be equal to $\sqrt{50^2+1000^2}=1000$ ohms approximately. With 100,000 volts impressed on this circuit, the current flow would be $\frac{100,000}{1000}=100$. If, in addition, the circuit contains an inductive reactance of 1000 ohms, it is evident that this entirely neutralizes the capacity reactance and that the current is only limited by the 50-ohm resistance, and thus in this case is equal to $\frac{100,000}{50}=2000$ amperes. With this current flowing, the voltage across either the inductance or capacity becomes equal to $2000\times1000=2,000,000$ volts, which of course would be far beyond destruction. Of course, this extreme condition does not apply to an ordinary transmission line, where the resistance, inductance and capacitance are distributed; but destructive voltages may be set up where inductance and capacitance are concentrated.

Fortunately, the characteristics of transmission systems are such that their inductive reactance is not large enough to neutralize the capacity reactance at the fundamental generator frequency. Since, however, the inductive reactance increases and the capacity reactance decreases in proportional to frequency, the two reactances come nearer together for high frequencies, such as for the high harmonics of the generator wave. These may, therefore, be the cause of resonance rise of voltage between the line capacity and circuit inductance. With modern alternators, however, the higher harmonics are generally so small that there is not much danger from resonance.

Abnormal voltages can also be caused by traveling waves which are set up when the equilibrium of an electric circuit is disturbed. Such disturbances may originate in the circuit itself, as by switching, or they may be due to external causes, such as atmospheric lightning phenomena.

When an electric circuit is connected to a generator or other source of energy, a wave of voltage and current shoots out along the line with a very high velocity, and charges the same. If the maximum value of the voltage is e and the maximum value of the current i, the wave possesses, per unit length, an electrostatic energy of $\frac{Ce^2}{2}$ watt seconds and an electromagnetic energy of $\frac{Li^2}{2}$ watt seconds, C being

the capacity in farads and L the inductance in henrys per unit length (cm.) of the circuit. These two quantities are equal, or $\frac{Li^2}{2}=\frac{Ce^2}{2}$, and the relation between the voltage and current at a certain point of the traveling wave is, therefore,

$$e=\sqrt{\frac{L}{C}}\,i.$$

$\sqrt{\frac{L}{C}}$ is termed the "natural impedance" of the circuit, and is of great value in the study of transient phenomena.

If the line is open-circuited at the farther end, it is obvious that when the wave reaches this point it cannot flow any further, but is

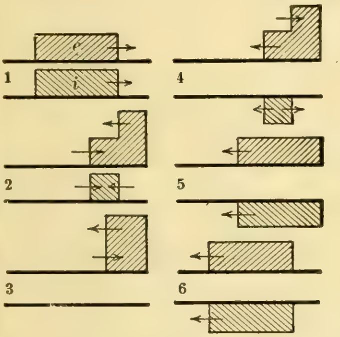


FIG. 408.—Reflection of a Traveling Wave at the Open-circuited End of a Line.

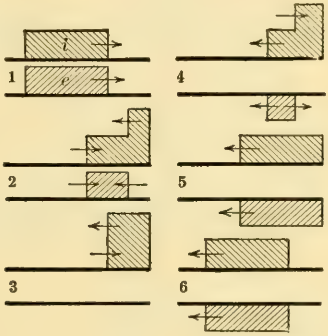


FIG. 409.—Reflection of a Traveling Wave at the Short-circuited End of a Line.

reflected, the voltage and current of the reflected wave being of the same values as in the original waves because the energy remains constant. The total current of the incoming and reflected wave must, however, be zero, on account of the open-circuited line, and the whole energy is, therefore, stored at this point in the electrostatic field. The reflected current wave must therefore be reversed and its value equal $-i$, while the value of the voltage wave at the end of the line where the original and reflected waves overlap is, therefore, equal to $2e$, as shown in Fig. 408.

When the end of the line is short-circuited, however, the conditions are entirely reversed. In that case the voltage at this point must be zero, and all the energy is stored in the electro-magnetic field, the value of the total current at the end of the line being equal to $2i$, Fig. 409.

The wave travels twice forth and back over the entire length of the

line, after which the conditions return to the same state as at the beginning (Fig. 410). It will, however, continue to oscillate back and forth until damped out by the resistance and leakage of the line, after which it assumes a stationary condition with a charge corresponding to the voltage of the generator.

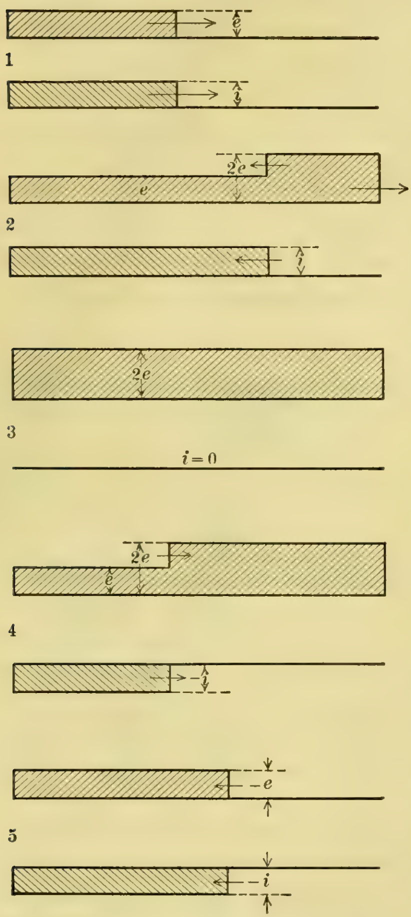


FIG. 410.—One Complete Oscillation of a Traveling Wave Set Up when Switching in an Open-circuited Line.

The wave length, or rather the distance which the wave front travels in completing the above cycle, is obviously equal to four times the length of the line, and the frequency of the oscillation is

$$\frac{v}{4l}=\frac{1}{4l\sqrt{LC}},$$

where l is the length of the line, and v or $\frac{1}{\sqrt{LC}}$ the velocity at which electric energy travels through a circuit whose inductance and capacity per unit length are L and C. This velocity for overhead lines is equal to the velocity of light, or 188,000 miles per second. The waves in the above illustrations are shown to have a rectangular form, which could only be the case if the generators had no resistance or inductance. Ordinarily, however, they are of a more or less sloping character.

In the above it was assumed that the end of the line was either open- or short-circuited. If a non-inductive resistance, R, is connected across the end of a line, the voltage of the reflected wave, and thus the total voltage at this point, necessarily depends on the value of this resistance. When $R=\infty$ it naturally resembles an open-circuit, in which case the maximum voltage is equal to double the normal value, while if $R=0$, or R is negligible, thus resembling a short-circuit, the

voltage is zero. With $R=\sqrt{\frac{L}{C}}$ there is no reflected wave at all. If $R>\sqrt{\frac{L}{C}}$ there is a partial reflection with reversal of current, while, if $R<\sqrt{\frac{L}{C}}$ there is a partial reflection with reversal of voltage. With an inductive receiving circuit, this acts in the first instant as a resistance of infinite value, and voltage reaches double value, while a condenser under similar conditions would act as a short circuit, and the voltage would be zero.

From the preceding it follows that when a dead high-tension transmission line is to be energized the best practice to follow is first to switch the line on to the dead transformers by means of the high-tension switch, and then to energize the combination of line and transformers by closing the low-tension switch to the generating source. This sequence of closing the switches will obviate the high-tension surges and, consequently, will minimize the danger of insulation breakdown.

It is also of greatest importance to consider the changes which take place at a transition point between two circuits of different characteristics, when a traveling wave passes from one to the other, as, for example, when an underground circuit joins an overhead, or where a transmission line is connected to a transformer.

Assume that a traveling wave with the voltage e and the current i approaches from a circuit having a natural impedance $Z_1=\sqrt{\frac{L_1}{C_1}}$ and enters a second circuit with a natural impedance of $Z_2=\sqrt{\frac{L_2}{C_2}}$. Part of the wave will then be reflected and part transmitted. It is also evident that at the transition point the potential will be the sum of the incoming and reflected waves, while the current will be represented by the difference of the two waves, since they travel in opposite directions. If we thus denote the voltage and current of the reflected wave by e_2 and i_2 and of the transmitted wave by e_1 and i_1, we get the following relation at the transition point.

$$e+e_2=e_1;$$

$$i-i_2=i_1;$$

but

$$i=\frac{e}{Z_1};$$

$$i_1=\frac{e_1}{Z_2};$$

$$i_2=\frac{e_2}{Z_1}.$$

The amplitude of the transmitted voltage wave is, therefore,

$$e_1=\frac{2Z_2}{Z_1+Z_2}\,e,$$

and of the reflected voltage wave

$$e_2=\frac{Z_2-Z_1}{Z_1+Z_2}\,e.$$

Similarly, we get for the current

$$\dot{i}_1=\frac{2Z_1}{Z_1+Z_2}\,\dot{i},$$

and

$$\dot{i}_2=\frac{Z_2-Z_1}{Z_1+Z_2}\,\dot{i}.$$

If, therefore, Z_2 has a higher value than Z_1, it follows that the voltage of the traveling wave is transmitted to the second circuit at an increased amplitude, and vice versa. A traveling wave originating in an underground cable will, therefore, enter an overhead circuit with an increase in voltage, while a wave originating in an overhead circuit will pass into a cable system with a lower voltage.

These relations between the reflected and transmitted waves and the incoming wave are, however, only applicable to cases where the wave, in passing the transition point, continues its travel in the form of a wave; that is, in case we have distributed inductance and capacity on both sides of the transition point. If, on the other hand, resistance, inductance and capacity are concentrated at the transition point, the conditions become entirely different, and it has been suggested that such a scheme should be used for protecting transformers and machinery against the traveling waves entering from the line. The use of inductance and capacity has been advocated for some time. Both have the properties of changing the wave front of the transmitted wave so that it begins with zero and rises gradually to its full value. The reflected wave, however, will have a rectangular or steep wave front, similar to the incoming wave.

The energy of the incoming wave is naturally also split up in two parts, corresponding to the transmitted and reflected waves, but there is no reduction in the total energy. This has led to the suggestion, by Gino Campos, to use a resistance shunted across an inductance (see Fig. 411). In addition to considerably smoothing out the wave front of the transmitted wave, it causes some of the electromagnetic energy to be dissipated. The inductance forces a wave with steep front to pass through the resistance. This, in turn, results in a drop in voltage

and gives the transmitted wave a lower value than the incoming, while on the other hand part of the energy of the wave is dissipated into heat. The working current, however, passes through the inductance with a negligible drop. This combination is connected in series with the line, as shown.

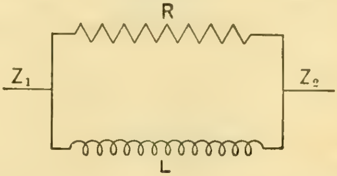


Fig. 411.—Protective Device, Consisting of an Inductance Shunted by a Resistance. This combination is for Series Connection in a Circuit.

Another combination consisting of a resistance in series with a condenser or capacitance, but connected between the line wires or between the line wires and ground, is shown in Fig. 412. Both of these devices or combinations are particularly effective as protective devices, as they dissipate the energy of high-frequency waves. They are, therefore, generally termed "high-frequency absorbers."

Figure 413 shows how the reflection and transmission of a traveling wave takes place in a particular case with inductance and resistance concentrated at the transition point. The amplitude of the waves, as well as their wave fronts, is, of course, dependent on the natural impedances of the circuits on either side of the transition point, as well as on the value of the inductance and resistance concentrated at this point. The calculations are of a rather intricate nature and beyond the scope of this book. It is seen, however, that with a protective device of this kind, both the transmitted and reflected waves have steep fronts, although of less height than the original wave. This has led to the suggestion of adding a condenser to Campos' combination, in which case the voltage at the front of both the reflected and transmitted waves would be zero. Both these devices are patented.

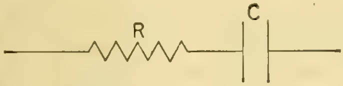


Fig. 412.—Protective Device, Consisting of a Capacitance in Series with a Resistance. This combination is Used in Shunt with a Circuit.

The above has dealt with the excess voltages which can occur when a line is connected to a source of energy. Dangerous voltages are, however, also liable to be set up when a loaded or short-circuited line is suddenly broken. In this case the voltage rise depends on the value of the interrupted current, and the rapidity with which the circuit is broken, and again on the natural impedance of the circuit.

It was previously shown that the energy of a circuit was stored in both the magnetic and dielectric fields, corresponding to the current and voltage values. At a certain instant, therefore, the two stored

quantities are equal, while if the current is zero all the energy must, of course, be stored in the dielectric field and vice versa. We thus had:

$$\frac{Li^2}{2}=\frac{Ce^2}{2},$$

and the relation betweeen voltage and current

$$e=\sqrt{\frac{L}{C}}\,i.$$

For transmission work the ratio

$$\frac{L}{C}=138\log\frac{D}{r}\text{ ohms,}$$

and this value generally falls between 400 and 200 ohms. For transformers, however, it is considerably higher, being around 3000, while an underground cable has a much lower natural impedance than an overhead circuit.

For example, if in a circuit having a natural impedance of 400 ohms, a current with a maximum value of 200 amperes is suddenly broken, the surge pressure cannot exceed 200 ×400=80,000 volts, because this is the maximum value of the voltage wave which is necessary for storing in the dielectric field the whole amount of energy which was previously stored in the electromagnetic field.

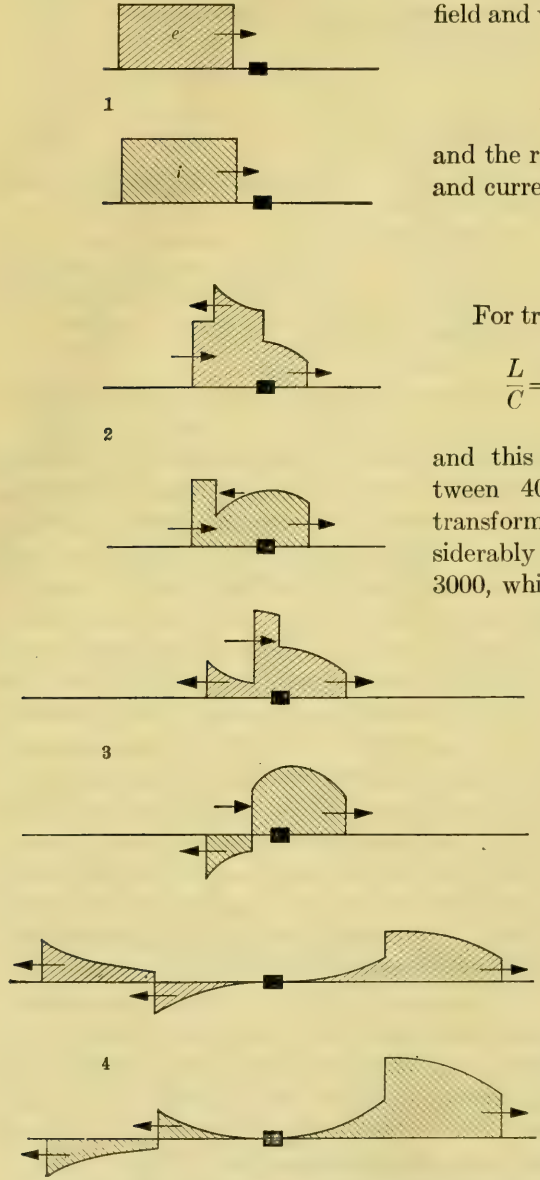


Fig. 413.—The Reflection and Transmission of a Traveling Wave with Concentrated Inductance and Resistance at the Transmission Point.

Traveling waves similar to the above are also set up by atmospheric lightning phenomena. The gradual accumulation of static charge on a line from the neighboring atmosphere increases its potential with respect to the earth, and this may ultimately become so great as to puncture the insulators. Suppose, now, that there is a lightning discharge between cloud and cloud or between cloud and ground. This is followed immediately by a redistribution of the electrostatic field, and a general equalization of potential occurs. The static charge so set free moves along the line as an impulse or traveling wave. Such waves may have a potential many times greater than that caused by switching, and they may have a very steep wave front and thus produce high potential differences between points along the conductor, for instance, across individual transformer coils or group of coils.

Several forms of protective devices of more or less value have been devised to guard against abnormal voltage conditions. Of these, the aluminum-cell and the oxide-film lightning arresters possess ideal characteristics for use against such high-voltage disturbances, where the excess voltage occurs between the phase conductors or between the phase conductors and ground. The films of the arrester introduce a barrier to the normal potential of the system, but allow the energy of an abnormal disturbance to discharge readily. The arrester is generally used in connection with choke coils, the function of which is to retard and reflect the incoming waves sufficiently to allow the arrester to better perform its duty.

Overhead ground wires are also very generally used to protect transmission lines against excessive static charges, the cost of high-voltage lightning arresters making their installation along the line impractical.

The nature of high-frequency disturbances is a comparatively recent discovery, and the means and methods for preventing them and protecting against them are still being studied and investigated. The greatest damage caused by such high-frequency disturbances has occurred in high-voltage transformers, as would naturally be expected. The best protection against them, therefore, is to insulate heavily the end turns and the individual coil groups, while inductances and energy-absorbing devices may, as stated, be advisable for further protection.

Lightning Arresters. Two types of lightning arresters are now in almost universal use, i.e., the electrolytic aluminum-cell arrester and the oxide film arrester. The latter has superseded the former and is being selected for all new installations; but as numerous aluminum-cell arresters are in use, a short description of this type will be given.

Aluminum-Cell Arresters: This type consists essentially of a stack

of aluminum cells with series gap, each cell consisting of two inverted, pre-treated aluminum cones, separated by insulating spacers, and the space between cones partially filled with electrolyte. Each stack of cells is immersed in a tank of oil to improve the insulation between cones, prevent evaporation of the electrolyte, and provide heat-absorbing capacity. Between the tank and cone stack is suspended an insulating tube, which improves the circulation of oil and increases the insulation between the tank and cone stack.

The cell stacks are arranged in sections, in such a manner that between any two lines of a circuit and any one line and ground there are two equal sections. In other words, for a three-phase system there are four sections to the arrester. The sections are suitably insulated from ground and connected to the line through series gaps equipped with charging contacts and resistances to minimize oscillations, and properly proportioned horn-sphere electrodes to give minimum dielectric spark lag. Two of the sections are connected to a transfer device, so arranged that when one is connected to the line the other is connected to ground.

The fundamental principle of the arrester is the film or valve action of the aluminum cell which depends on an electro-chemical action between the electrolyte and pre-treated aluminum cone. This film offers a high resistance to current at normal voltages but practically no resistance to currents at high voltages such as those induced by lightning. The film therefore quickly relieves the line of high abnormal voltages, and breaks the arc to ground as soon as the voltage falls to normal. To keep this film properly formed, it is necessary to connect each section of the arrester directly to the line, one or more times a day. This is easily done by revolving one side of each gap, with the operating mechanism provided, until the charging contacts short-circuit the gap. The gaps are shorted for at least five seconds; then they are opened to disconnecting position and the transfer device operated. The gaps are again shorted for at least five seconds, then opened to the normal operating position.

Figure 414 shows a section through one of the tanks of a high-voltage aluminum-cell arrester.

Oxide Film Arresters. This type of arrester consists essentially of a number of cells with a gap in series between line and ground. The cells are held together under slight pressure and are arranged in sections or stacks, according to the voltage and kind of circuit. The cells are disc-shaped, about $7\frac{1}{2}$ inches in diameter and $\frac{5}{8}$ inch thick. Each cell is made of two circular brass plates crimped firmly to the edges of an annular piece of porcelain. A powder, lead peroxide, which has very

low resistance, compactly fills the space between the plates, and the inside of the metal plates is covered with a varnish film which is an

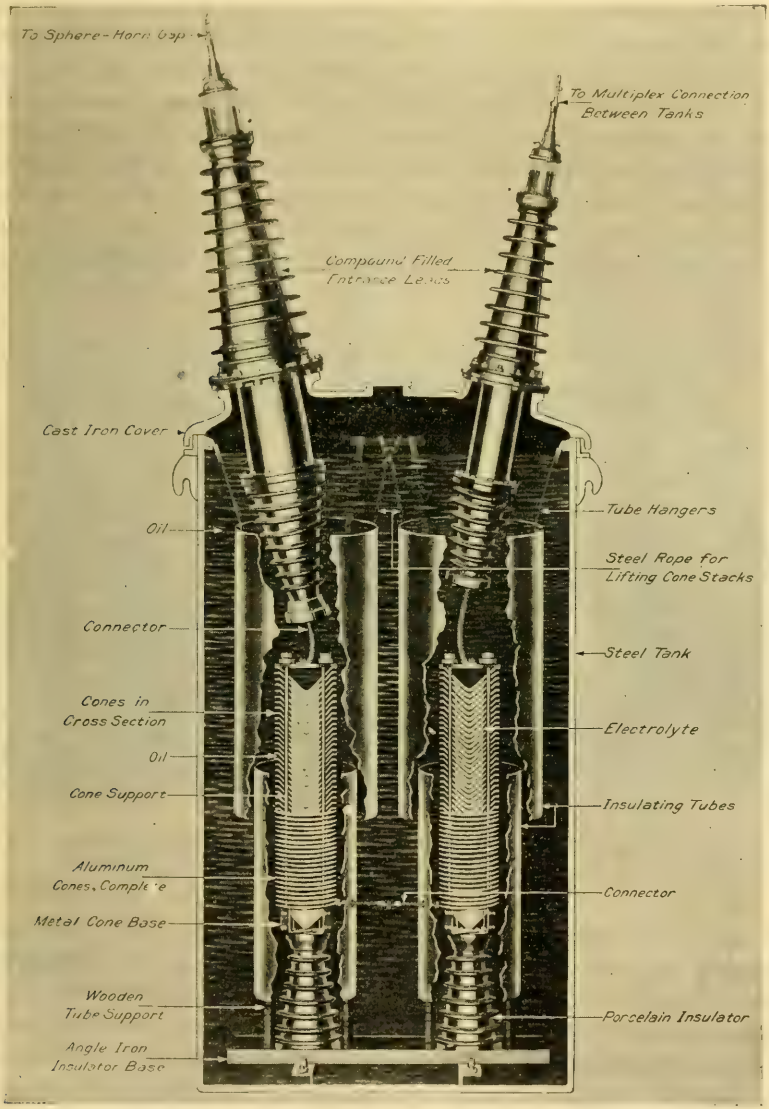


FIG. 414.—Section through Tank of 130,000-volt Aluminum-cell Lightning Arrester.

insulator. The number of cells used in an arrester is such that the voltage per cell is approximately 300 volts.

When a lightning voltage sparks over the gaps, it is impressed on

the cells and breaks down the insulating coating on the metal plates. The breakdown occurs in the form of a small puncture of the film coating, but the metal plates are not punctured. As soon as the film gives way, a discharge current flows through the cells to ground, thus relieving the lightning pressure. The flow of current through the cells immediately causes a chemical change, by heat, in the lead peroxide at the point of puncture. The lead peroxide is changed to red lead and litharge, which have a very high resistance. Thus, following the lightning discharge, a very high resistance, amounting practically to insulation, is automatically cut into the discharge path. This cuts off the flow of generator current that would otherwise follow the lightning dis-

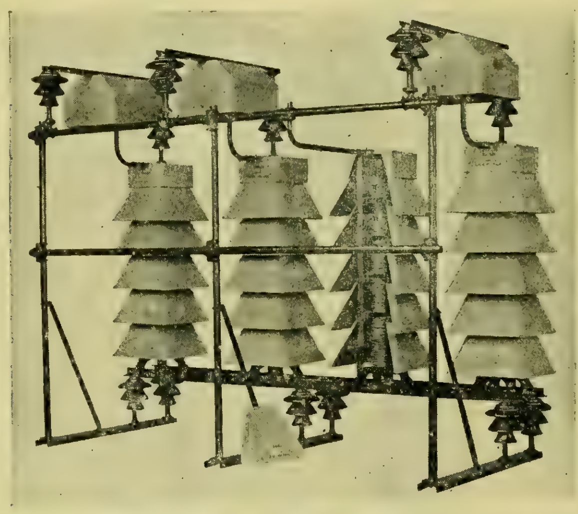


Fig. 415.—Outdoor Oxide Film Lightning Arrester. Typical Construction up to 73,000 Volts. (Second Stack from Right Shows Exposed Cells.)

charge, and the arcs in the gaps die out. If the potential should still, or again, be sufficiently high to break down the gaps, the operation is repeated at some other point on the surface of the varnished plates.

The arrester requires no more than the usual inspection and attention given to other kinds of electrical apparatus, except that an inspection should always be made at the beginning and end of each lightning season.

A means is provided for occasionally testing the cells of arresters for voltages above 7500, to determine whether any have deteriorated to such an extent as to be useless. This device consists of a calibrated gap in a glass vacuum bulb mounted on a testing stick, with contacts

which can be placed against the metal plates of the cell. The arrester is short-circuited on the line, and this causes a drop across the cells in proportion to their resistance. A cell of high resistance will have a large drop and will cause the bulb to glow. The cell can then be easily removed and a new one inserted. It is recommended that the arrester be tested only at the beginning and end of each lightning season.

The cells are connected in the familiar multiple arrangement, which gives, for three-phase arresters, two sections of cells between any pair of lines and two sections between any line and ground. The arrester

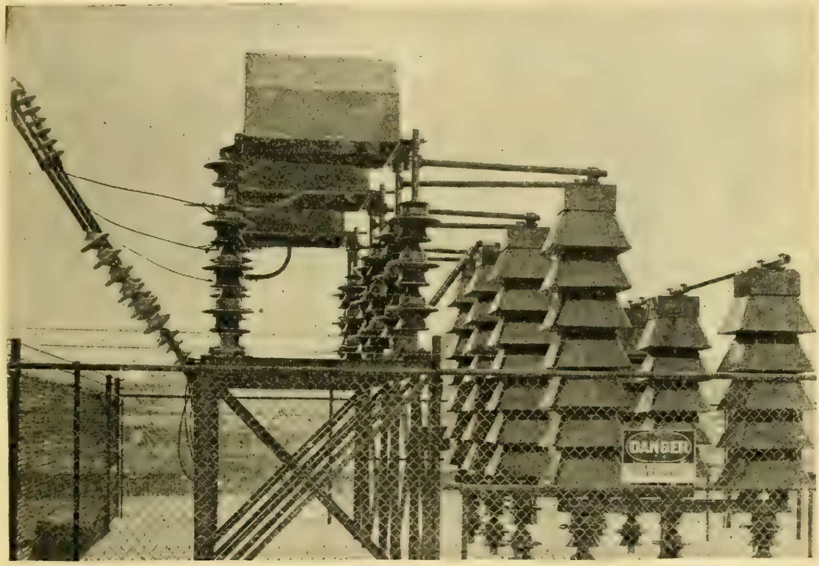


Fig. 416.—Oxide Film Lightning Arrester Installation. Typical for Voltages above 73,000.

therefore consists of four legs arranged in four stacks for voltages up to 73,000 (see Fig. 415); while for higher voltages each leg is arranged for two stacks (see Fig. 416) to secure the desired mechanical stability. The stacks are mounted on insulating racks, and arresters for outdoor service have galvanized sheet-iron louvres attached to the wooden supports, to give protection against the weather, as shown in the illustrations. These louvres can readily be removed for inspection or repairs.

All oxide film arresters for voltages above 7500 are connected to the lines through spark gaps of a hemisphere type, as shown in Fig. 417. The small leakage current with this type of arrester makes it unneces-

sary to use horn gaps to aid in breaking the arc, and it is furthermore possible to cover the gap. This is of the utmost importance for outdoor arresters, as rain greatly lowers the 60-cycle spark-over voltage of all uncovered gaps, and thus imposes an increased setting and consequently decreased protective value of the arrester, since the high-frequency lightning spark-over voltage is not changed by rain. The covered sphere gap, therefore, gives the maximum protection, since it can be set for a minimum voltage value with dry weather, and the protective value will be constant under all conditions.

Sphere gaps [1] give the highest obtainable speed (or minimum time-lag) of discharge from the most dangerous kind of lightning disturbances, i.e., impulses of steep wave front. When a 60-cycle voltage is slowly applied to a gap and gradually increased, spark-over will occur

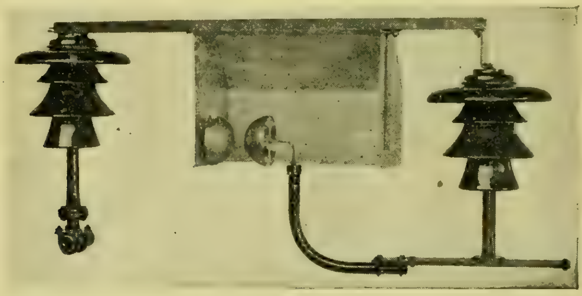


FIG. 417.—Covered Hemisphere Gap as Used on Outdoor Oxide Film Lightning Arresters; 37,000 to 73,000 Volts.

at some definite voltage. This is the minimum voltage that will cause sufficient ionization for the gap to discharge, and it requires a relatively long time.

Lightning voltages, or voltages of relatively steep wave front, start at zero or line voltage and increase at the very rapid rate of millions or billions of volts per second. When such voltages are applied across an ordinary gap or insulator, spark-over does not occur at the instant the minimum or 60-cycle voltage is reached, as considerable time is required at this voltage. When this voltage is reached, the spark begins to form but is only completed after the rapidly rising voltage has reached some higher value. The "slower" the gap, the higher the voltage will rise, and two gaps or insulators with equal 60-cycle spark-over voltages may therefore have entirely different lightning or impulse spark-over voltages, because of the time lag. It is greatest in

[1] Peek, A. I. E. E., June, 1919.

a non-uniform field or for electrodes where corona precedes spark-over, such as the needle gap; it is a minimum for a uniform field, such as is obtained by the sphere gap.

The ratio between the impulse and 60-cycle spark-over voltage is termed "impulse ratio." Where there is no time lag, the impulse ratio is unity; the greater the time lag, the higher the impulse ratio.

It is very important to utilize these principles in design of high-voltage apparatus. Protective gaps, for example, should thus have an impulse ratio of unity or low lightning spark-over voltage, while

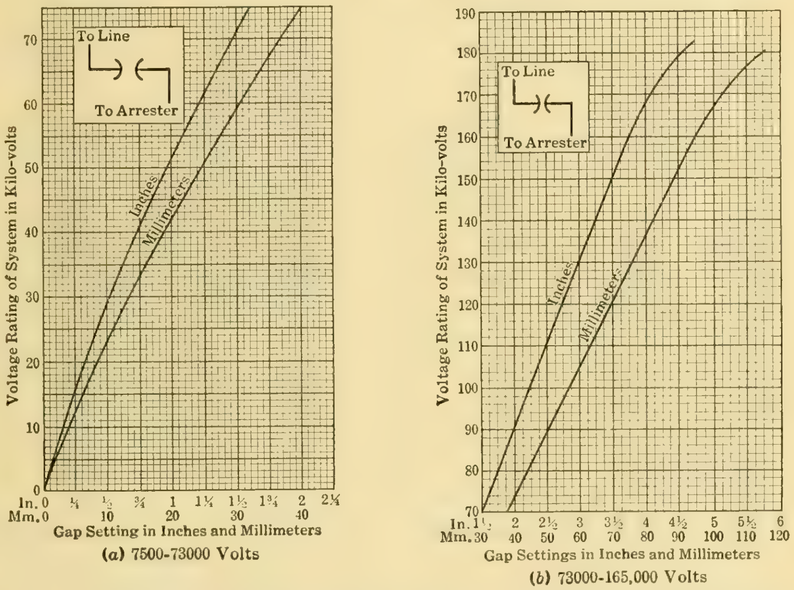


FIG. 418.—Sphere-gap Settings for Indoor and Outdoor Oxide-Film Lightning Arresters.

insulators, bushings and other insulation should have a high impulse ratio or high lightning spark-over and puncture voltage.

The spark potential of the gaps is affected by several variables, such as the shape of the generator potential wave, altitude, moisture, pitting or accumulation of foreign matter on the gap electrodes, shape and size of gap electrodes and location of the gaps with regard to metallic objects. The curves in Fig. 418 are the settings recommended by the manufacturer, and are based on a careful consideration of the above points, together with actual test results and experience. Gap settings should be for the maximum operating voltage, that is, the maximum voltage attained at the main generating station supplying power to

the system. Arresters which are operated temporarily at lower voltages should have their gaps adjusted for such lower-voltage operation.

Oxide film arresters, as normally rated, have insulation suitable for any altitude up to 4000 feet. Above this, increased insulation may be required and the gap-settings should be corrected for altitude, in accordance with the following correction factors:

ALTITUDE CORRECTION

Sea level to 1000	—Use curves.	5000 to 7000 ft.	Add 30 per cent.
1000 to 3000 ft.	Add 10 per cent.	7000 to 9000 ft.	Add 40 per cent.
3000 to 5000 ft.	Add 20 per cent.	9000 to 11000 ft.	Add 50 per cent.

Oxide film arresters do not require charging like the aluminum-cell arrester, and the absence of oil reduces the fire hazard.

An arrester should not be applied to a circuit outside of the range of voltage indicated by the manufacturer. If it is used on a lower voltage, the protection will not be so good as could be obtained, while if used on a higher voltage the arrester will be too sensitive and will probably be damaged. Arresters should further be selected without regard to line drop, and if, as on some large transmission systems, there is a rise in voltage at light loads, due to capacitance, the maximum voltage should govern the selection of the arrester. If the line voltage is about on the dividing line between two ratings, the arrester of the higher rating should be selected. Operators are occasionally inclined to rate their systems according to the nominal voltage, whereas the actual voltage may be 5 to 10 per cent higher. In any instance, the maximum voltage should govern the selection of the arrester.

When it is desired to operate an oxide film arrester temporarily at one voltage and later at another (higher) voltage, either one of two courses may be followed. If the time of operation at the lower voltage is to be short, the arrester may be purchased complete for the ultimate voltage, and the excess cells temporarily short-circuited. If the time is a matter of two or three years, some expense in the original installation can be saved by purchasing an arrester for the ultimate voltage, but with only sufficient cells for the temporary voltage. In the latter case, the arrester is otherwise the same as the arrester for the ultimate voltage, metal spacers and connectors being used to compensate for the omitted cells.

If oxide film arresters are to be installed where the insulators will be subjected to cement dust, acid fumes, etc., the standard arresters should not be used, but special arresters equipped with insulators sufficiently large to compensate, so far as is practicable, for the reduction in insulating strength. In such cases, it is desirable for the ar-

rester manufacturer to know what kind of insulators are used on the lines tapped by the arrester, so that the arrester insulation may be made of comparable strength.

The wiring connections of lightning arresters are important. The discharge circuit should contain minimum impedance, and hence must furnish the shortest and most direct path from line to ground. The most severe disturbances which an arrester is called upon to handle are of high frequencies, and it is therefore imperative to eliminate all necessary inductance. The features favorable for low inductance are short length of conductor, large radius bends and large surface of conductor. Copper tubing is strongly recommended for wiring high-voltage arresters. It has the advantage over either copper strip or solid con-

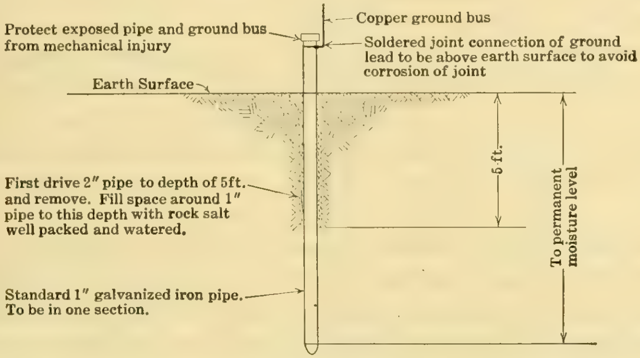


FIG. 419.—Method of Making Pipe Ground for Lightning Arresters.

ductors in that it is easily supported, requires fewer insulators, and is therefore cheaper to install.

In all lightning arrester installations, good, permanent, low-resistance grounds are essential for the satisfactory operation of the arresters. Poor grounds cause loss in protection, with an ultimate loss in apparatus. Satisfactory grounds (see Fig. 419) can be made by driving a 1-inch iron pipe to the permanent moisture level and then salting the ground around the pipe to a depth of several feet. The ground should be kept thoroughly moistened. Two or more of such ground pipes, spaced at least 6 feet apart to get the maximum benefit of each, and bussed together by means of heavy copper wire, or preferably flat copper strip, make an excellent arrangement for a station ground.

Preliminary to the actual installation of the ground elements, a survey should be made to determine the character of the soil, depth to permanent water or moisture level, and the general topography of the

section. The purpose of this survey is to preclude the possibility of installing grounds in a pocket of earth entirely isolated by rock strata from the main earth section, and thus obtaining false indications. Valuable data along these lines can be obtained from the United States Geological Survey Reports and also from the city and county engineering department records. In many cases an actual investigation will have to be made.

The number of arrester grounds required depends upon the character of the soil and the size of the arrester installation. For the average power or lighting station, the installation of four such ground pipe arrangements as described above should be sufficient. These should be located near each outside wall of the station and solidly bussed together. One of these groups should be installed at a point nearest the arrester, or a fifth put in at such a point. It is advisable to connect these earth pipes to the iron framework of the station, and also to any water mains, metal flumes, or trolley rails that are available. In no case should there be less than two pipe grounds installed, and, where accurate records are to be kept of ground resistance, at least three such pipe grounds should be made, with the individual pipes at least 6 feet apart.

It is of prime importance that some systematic examination of the grounds and ground connections be made. A record kept on file and showing exact plans of the location of the ground plates, ground wires, and pipes, with a brief description, will be of considerable value in this work. The actual electrical efficiency of the ground connection can only be determined by a measurement of its resistance. The resistance of a single pipe ground, properly installed and maintained, has an average value of about 15 ohms. Where there are at least three ground pipes or plates, not less than 6 feet apart, the actual resistance of each ground can readily and accurately be determined. With three grounds identified as A, B, and C, the series resistance of $A+B$, $B+C$, and $C+A$, can be obtained by the fall-of-potential method. Solution of the three equations will give the individual resistances. The method of measuring in detail is as follows: Connect a 110- or 220-volt A.C. or D.C. supply through a regulating rheostat and an ammeter across two of the ground pipes. The function of the rheostat is to limit the current to a safe value (5 to 10 amperes) in case the ground is of low resistance. The drop across the two grounds should be measured by a suitable voltmeter, allowing a few minutes after closing the circuit for constant conditions to be reached. The voltage drop divided by the current gives the resistance of the two grounds in series.

For example, assuming the three grounds, as A, B, and C, measured

with a current of 5 amperes and a drop of 80 volts across $A+B$. This gives a total value of resistance of $A+B$ of 16 ohms. Similar measurements show $B+C$ equals 18 ohms and $C+A$ equals 10 ohms. Thus,

$$A+B=16, \quad \ldots \ldots \quad (1)$$

$$B+C=18, \quad \ldots \ldots \quad (2)$$

$$C+A=10, \quad \ldots \ldots \quad (3)$$

Subtracting equation (1) from (2),

$$C-A=2 \quad \ldots \ldots \quad (4)$$

Adding equations (3) and (4),

$$C=6 \text{ ohms.}$$

Substituting $C=6$ in equation (2),

$$B=12 \text{ ohms.}$$

Substituting $C=6$ in equation (3),

$$A=4 \text{ ohms.}$$

Where there are but two grounds available, this method will only allow the total resistance of the two grounds to be determined. It is evident, however, that this will indicate a high resistance in either ground, if such exists. Also, if the two grounds are operated in parallel, the maximum value of operating resistance can be but one-fourth of the measured series resistance.

A more approximate method of keeping account of the condition of the earth connections is to divide the earth pipes into two groups and connect each group to opposite sides of a 110-volt lighting circuit with an ammeter in series. A current flow of 20 amperes indicates a satisfactory condition, provided the earth pipes are properly distributed around the station.

Choke Coils. Choke coils are recommended for use with all high-voltage lightning arresters when used on overhead lines. They should not, without careful consideration, be installed with lightning arresters which are used to protect cables over half a mile long.

The choke coils should be located between the arresters and the apparatus to be protected, so that an incoming surge will meet first the arrester and then the choke coils. The functions of the choke coil are to hold back the lightning disturbance from the generator or transformer until the arrester has time to discharge to earth, and to lower the frequency of whatever part of the disturbance passes through the

coil, so that the wave front is not so steep as to cause a serious rise in potential across the end coils of the transformers or generators.

Choke coils for high-voltage work are of two general designs, the stationary type (Fig. 420) and the suspension type (Fig. 421). The stationary choke coil is formed of bare copper wire, supported on insulators which are mounted on steel bases. The indoor coils have post insulators; the outdoor coils, petticoat insulators. The advantage of this type of choke coil is that the turns are air insulated from each other. Should there be arcing between turns in the case of extremely heavy disturbances, the turns will immediately re-insulate themselves.

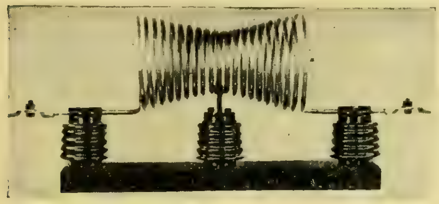


Fig. 420.—25,000 Volt Stationary Type Choke Coil.

The suspension choke coil consists of a strain insulator having a bare copper coil wound concentric with its axis. The coil is held securely at each end and is kept from sagging in the center by one or more brackets.

Figure 422 shows a thunderstorm map for the years 1904–1913, as prepared by the U. S. Weather Bureau.

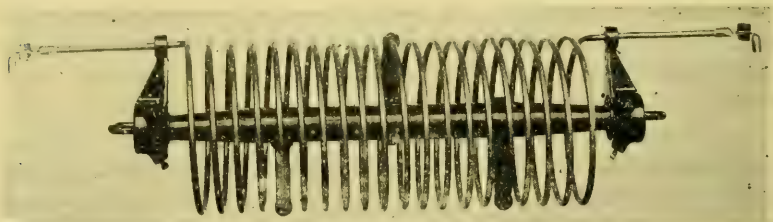


Fig. 421.—Strain-type Suspension Choke Coil for Station or Outdoor Service.

Arcing Ground Suppressor. Arcing ground suppressors, as well as short-circuit suppressors, described in the next section, are used to a limited extent for protecting line insulators against arcs and the consequent vicious surges accompanying such accidental arcs, which generally follow after lightning discharges.

The arcing ground suppressor, as described in the following, is intended to be used with non-grounded systems. Its use is also limited to steel tower lines, as on a wood-pole line the resistance of the pole is liable to prevent sufficient current flowing to ground to reduce the potential sufficiently to operate the relay.

The arcing ground suppressor, as generally built, consists of three single-pole, independent, motor-operated oil switches, electrically and mechanically interlocked, to prevent more than one operating at the

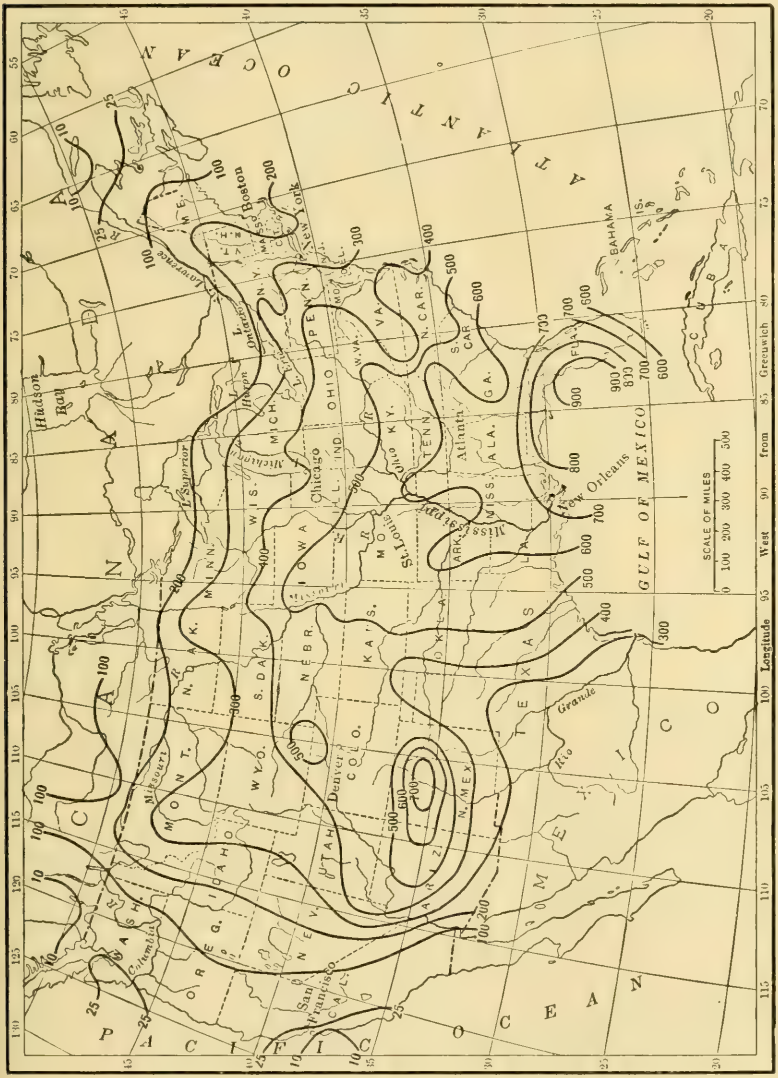


FIG. 422.—Thunderstorm Map, 1904–1913, U. S. Weather Bureau.
Figures indicate total number of thunderstorms during the 10-year period.

same time. Each switch is connected to ground on one side and to the line on the other. The suppressor is controlled by a phase-selecting relay, which remains inactive while the system is balanced; but when it becomes unbalanced, because of a ground on one phase, it operates

the corresponding phase of the suppressor, which, in turn, grounds the same phase of the line, thus shunting the current and extinguishing the arc. The switch is then automatically opened and will remain so, provided that the ground was only temporary, such as an insulator spilling over. If the ground is of a permanent nature, as when caused by the puncture of an insulator, the switch will immediately close a second time and be locked in the closed position until opened by hand after the ground has been removed. Should the switch stay open for a fraction of a second after the first stroke, however, the "second stroke device" would become inoperative, as it only comes into action when the switch starts to close the second time immediately after the first time. To prevent the possible operation of the suppressor in cases of

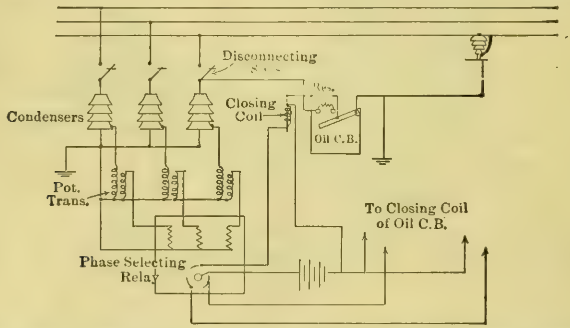


FIG. 423.—Elementary Diagram of Arcing Ground Suppressor.

short-circuits, an overload relay, which opens the control circuit of the suppressor may be provided.

Figure 423 shows an elementary diagram of an arcing ground suppressor.

Short-circuit Suppressor. This device operates on the same principle as the arcing ground suppressor, but it is intended for use on grounded systems where any arc to ground would form a short-circuit. The suppressor is connected between each line wire and ground, and consists of a fuse in series with a gap which is instantly closed when a short-circuit, caused by an arc-over or ground, occurs. The arc is thus shunted until the fuse blows, which gives sufficient time to allow the arc to extinguish itself. For a single-phase short-circuit, two of the fuses will blow, and for a three-phase short-circuit all three fuses. If the trouble does not clear itself or if there is a dead ground, of course, the main oil circuit breaker will finally disconnect the entire circuit as usual.

Protection of Telephone Lines. Telephone lines of power systems, running parallel to high-tension transmission lines, are subjected to

influences which may, under certain conditions, interfere with the proper transmission of speech. Under normal operating conditions, that is, with fairly well-balanced three-phase circuits, this influence will be slight, but with abnormal operating conditions on the transmission line the effect created on a telephone line may increase to such an extent as to become destructive. In addition to these influences, the telephone line is subjected to disturbances occasioned by lightning discharges, which, however, are very similar in character to the effects created by abnormal conditions on the transmission line, that is, during the time of switching with unbalanced phases or arcing grounds, etc.

Under normal operating conditions, the effect of the static induction upon the two wires of the telephone line is practically the same, with the result that the two wires will assume a certain potential with regard to earth. With a well-insulated and properly transposed metallic line, the potentials of each wire against ground will be nearly alike, and hence there will be no difference of potential between the two wires themselves. In telephone work, however, even the smallest difference of potential between the wires will create a flow of current through the telephone receiver. This current, being alternating, produces a noise in the receiver which may be loud enough to make talking impossible. The higher the voltage of a transmission line and the closer the telephone line is located to the same, the more prominent will be the noise in the telephone, with slightly unbalanced telephone lines. As this disturbing current is due to a difference of potential, it is obvious that the noise in the receiver is in a measure independent of the absolute value of the voltage on each line to ground, and that it cannot be eliminated unless the voltage on both wires be made exactly alike. This condition, which is termed "balanced," is realized by properly insulating and transposing the telephone lines. The larger the number of transpositions per mile, the more will the potential on the wires be equalized; and the better the insulation of the lines, the less chance will there be for a leak to ground, causing a drop of potential on that particular wire, with a subsequent result of unbalancing the line and rendering it noisy.

From the above, it will be seen that as far as the noise on the line is concerned it can be kept down within any limits, provided the telephone line is properly transposed and substantially insulated. On the other hand, it will be seen that the existing potential between telephone lines and ground, by reaching high values may not necessarily impair the transmission of speech, but will seriously strain the insulation of the instruments and make the use of the same by the operators dangerous.

Various schemes and devices have been developed for the protection of telephone lines, with more or less satisfactory results. The proper protective equipment to be used depends entirely on the arrangement of the lines and the abnormal conditions against which it is required to protect.

For lightning disturbances only, the standard vacuum gap gives the best and most reliable discharge path for these potentials to ground. On the other hand, where there are induced potentials in the telephone line, either between lines or from lines to ground, due either to electromagnetic or electrostatic induction, a multi-gap arrester, with knurled cylinders for the electrodes, is used between lines and ground. This is to avoid continual grounding of the telephone lines through the low breakdown path of the vacuum arrester, due to the induced potential to ground which may be of quite high value. The vacuum gap is put across the telephone lines where the induced potentials can be controlled by careful transposition. Here the vacuum arrester holds the voltage across the telephone apparatus to a value below its breakdown.

Where there is any possibility of induction trouble (and this may occur up to one-quarter or one-half mile away from the power circuit under abnormal conditions) the telephone line insulating transformer is of prime importance. This provides an insulation barrier of 25,000 volts test between the telephone instruments and the lines. On the line side of these transformers, which should be used at every telephone station, are installed the combined multi-gap and vacuum-gap unit which holds the voltages to ground and between lines to moderate values. In series with this in the telephone lines are fused switches for cutting off the apparatus in case of heavy continued discharges through the gaps, caused by induced potentials or crosses. They can also be operated as straight switches to cut off the station in any emergency.

As a further protection in case of induced potentials, particularly for potentials to earth, the drainage coil or bleeding coil can be used. These should be few in number, usually two, as too many will seriously affect the operation of the telephone circuits. These coils give a high impedance path across the telephone line, thus shunting the high-frequency talking currents, but provide at the same time a low impedance path for the flow of equal currents from both lines to ground at the center of the coil. These coils, where used, should be protected by cut-outs to guard against burn-out from heavy currents under abnormal conditions on the power line.

With the addition of possible crosses with the power line, the only additional feature to the above scheme is the double-pole horn gap

which serves as an auxiliary protection to the telephone line insulation until the telephone or power lines burn off. Where there is a cross but no paralleling, it is only necessary to use the fused switch on either side of the cross to isolate this section in case of a break.

From the standpoint of protection, telephone circuits can be classified as follows:

Class 1. Telephone circuits which do not cross or parallel power lines.

Class 2. Telephone circuits which cross but do not parallel power lines.

Class 3. Telephone circuits which parallel power lines but are not on the same towers or poles and do not cross power lines.

Class 4. Telephone circuits which are on the towers or poles with the power lines.

This classification covers every possible case, from a telephone line far removed from the power circuit to one mounted on the transmission towers themselves. Classes 3 and 4 are the most common. The sources of trouble vary from lightning only in Class 1, to lightning, crosses, and induction in Class 4.

The recommendations for the protection of the telephone circuit, according to the classification into which the circuit falls, are as follows:

Class 1. Telephone circuits which do not parallel or cross power lines.

Disturbances: Lightning.
Recommendations: Vacuum-tube lightning arresters from each line to ground at all telephone stations.

Class 2. Telephone circuits which cross but do not parallel power lines.

Disturbances: These circuits are subject to lightning disturbances and to contact with high-voltage power lines through broken wires, etc. They are not subject, to any extent, to electromagnetic or electrostatic induction.
Recommendations:

1. Combined double-pole fused switch and vacuum-tube lightning arrester in series with the main telephone line on both sides of crossing at nearest telephone stations.
2. Combined vacuum-tube and air-gap lightning arresters at all other stations.

Class 3. Telephone circuits which parallel power lines, but are not on the same towers or poles and do not cross power lines.

Disturbances: These circuits are subject to lightning disturbances, and electromagnetic and electrostatic induction. They are not subject to contact with the power lines.

Recommendations:

1. Insulating transformers at all telephone stations.
2. Combined double-pole fused switch and vacuum-tube lightning arrester at all telephone stations on the line side of the insulating transformer.
3. Drainage coils, preferably one at each end of line.

A diagram of connections for the apparatus used on this class of telephone circuits is shown in Fig. 424. The double-pole horn gap shown on the diagram is not used on this class of circuit, but on circuits coming under Class 4.

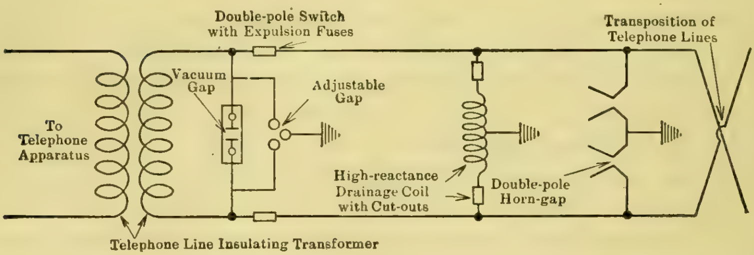


Fig. 424.—Diagram of Connections for Protective Apparatus Recommended for Telephone Lines, Classes 3 and 4.

Class 4. Telephone circuits which are carried on the towers or poles with the power lines.

Disturbances: These circuits are subject to lightning disturbances, electrostatic and electromagnetic induction, and to crosses with the power lines.

Recommendations:

1. Insulating transformers at all telephone stations.
2. Combined double-pole fused switch and vacuum-tube lightning arrester at all telephone stations on the line side of the insulating transformer.
3. Double-pole horn gap across line at each station on line side of all other apparatus for the protection of insulators on telephone circuit in case of crosses with power lines after series fuses are blown.
4. Drainage coils installed with fuses at each end of line; possibly an additional coil at the middle if the voltage to ground is not held to a safe value by two coils.

10. STATION WIRING

Experience has shown that in a great number of instances the shutdown of power plants has been caused by a defective installation of the station wiring. The design and construction of the cabling and wiring system of a station is, however, as important as that of the rest of the equipment.

It is obvious that the main electrical conductors should be of such a character and so installed as to minimize, as far as possible, any trouble from short-circuits or grounds, and particularly to confine such disturbances, in the event of their occurrence, to the circuit affected. It is likewise apparent that those buses or circuits on which a short would mean a complete station interruption should be still better insulated and protected.

The general practice of not providing automatic protection on the excitation system makes it essential to properly install all the exciter field circuits and to provide sufficient insulation to care for the high inductive voltage inherent in field circuits. The safety of the instrument and control system wiring should furthermore not be neglected, because in the event of trouble the main circuits may become involved through the accidental operation of an oil switch or the failure of a switch to open on an outside short-circuit. Every cable and wire should, therefore, have a definite place provided for it in advance, just as much as any other piece of machinery, and wires carrying currents of different voltages should, as far as possible, be kept apart from each other.

Insulation. The principal materials used for cable insulation are: rubber compound, saturated paper, and varnished cambric. Rubber insulation is commonly used on low-voltage cables of small size—say up to 600 volts and No. 0000 B. & S. For larger sizes and higher voltages, either paper or varnished cambric insulation may be used. The latter is very much less hydroscopic than paper insulation. In fact, while not offered as being waterproof in itself without a lead sheath, it is nevertheless sufficiently moisture-resisting to be largely used in braided form in relatively dry places. When it is used in lead-covered form, there is little likelihood that the ends of the cable will absorb an appreciable amount of moisture, while open for the purpose of jointing or terminating. This type of cable is likewise mechanically stronger and less likely to have the insulation injured during installation.

Of two cables—the one insulated with paper and the other insulated with varnished cloth—each properly proportioned to stand the working pressure and the same factory tests, if each is installed by the same

installation gang and under the same conditions, that insulated with varnished cloth will have the greater factor of safety after installation, for the reason just mentioned; that is, it is less likely to be injured by bending and less likely to absorb moisture while the ends are open. It, therefore, does not require so much skill in handling and jointing. Varnished cloth insulation likewise has the characteristic of being better able safely to withstand, temporarily, higher voltage surges without injury than either rubber or paper insulation.

When cables are run exposed, the insulation should be protected by a good fireproof covering of asbestos, so that in case of a short-circuit the trouble will not be communicated to adjacent circuits. When run in conduit or ducts, this type of covering absorbs moisture, and the weatherproof covering should be substituted; as a matter of fact, a lead covering is usually required for damp places.

All lead-covered cables should be provided with endbells for preventing moisture from entering the cable at the ends. These endbells and terminals may be designed for either horizontal or inverted positions and for convenient connections to the machine terminals or busbars.

Open Wiring. If the number of cables in close proximity does not make the run too congested or hazardous, it may be permissible to use wires or cables insulated for full potential, rigidly supported on insulators, also good for full-working potential. This arrangement gives double protection, since either the insulation or the insulators afford sufficient protection in case one should fail. On the other hand, the runs, being exposed, are under constant observation. Where the conductor does not exceed No. 0000 B. & S. size, it should be solid and not stranded, the solid form, of course, being more rigid. Where the amount of current to be carried is large, copper bars are used. This is usually the case with busbars. They are seldom insulated because the addition of insulation on a group of bars greatly reduces their carrying capacity by stopping the air circulation between the laminations.

Where the voltage exceeds 13,200, bare conductors consisting of solid wire, copper tubing or iron pipe are generally employed. The use of tubing or pipe makes it possible to reduce the number of expensive insulators for supporting it. To insulate such high-voltage conductors is expensive and quite unnecessary, because when properly installed they are widely spaced and kept well away from the floor.

Table LII gives dimensions for the spacing of rigid conductors. These values are based on striking distances between points, and are for guidance in determining proper distances between conductors and for general construction work.

TABLE LII

SPACING OF RIGID CONDUCTORS

Voltage Range.	Dimensions in Inches.			
	Outdoors.		Indoors.	
	To Ground.	Between Live Parts.	To Ground.	Between Live Parts.
2,000 to 3,500	3½	4	3	3½
3,501 to 7,500	5½	6	4½	5½
7,501 to 15,000	9	10	7	9
15,001 to 25,000	14	15½	10½	14
25,001 to 37,000	19½	22	14½	19½
37,001 to 50,000	25½	29	19	25½
50,001 to 73,000	36	41	27	36
73,001 to 95,000	47	53	34½	47
95,001 to 115,000	56	64	41	56
115,001 to 135,000	66	75	48	66
135,001 to 155,000	75	86	55	75
155,001 to 175,000	85	97	62	85
175,001 to 195,000	94	108	69	94

CORRECTION FOR ALTITUDE

Sea level to 1000 feet—Use table.
1000 to 3000 feet—Add 10 per cent to spacing in table.
3001 to 5000 feet—Add 20 per cent to spacing in table.
5001 to 7000 feet—Add 30 per cent to spacing in table.
7001 to 9000 feet—Add 40 per cent to spacing in table.

Cable should be supported every 4 feet in vertical runs and every 3 feet in horizontal runs, while for tubing the distance between the insulators may be increased to about 10 feet. When dealing with large conductors carrying heavy currents, care should be taken, as explained under the section of " Current Limiting Reactors," to rigidly support them so that they will not be torn from their supports when severe short-circuits occur.

Cables in Ducts or Conduits. It is not always convenient or desirable to run all of the conductors exposed, for several reasons. There may be no suitable place to support such cables. The congestion may be so great that it would be hazardous in other respects. They may be subject to mechanical injury. They may be in a bad location from a " safety first " standpoint. If, therefore, for any of the above reasons it is undesirable to run conductors exposed, they may be run in conduit or ducts and may be provided with a protecting weatherproof braid or lead sheath as the occasion demands. It should be borne in mind that if the lead sheath is omitted the conduit or ducts should be thoroughly drained to some pit so that water cannot remain in them.

Iron conduit should not be employed on alternating currents unless all conductors of the circuit are in the same conduit. The general practice is to use iron conduit up to about 2 inches in diameter, above which fiber conduit is generally used.

This type of conduit is formed in cylindrieal shape from fiber or wood pulp under pressure. The pulp is thoroughly saturated with a bituminous compound so as to kill any vegetable matter or bacteria which would tend to promote decay.

It has been found that the majority of all initial cable troubles are directly traceable to some injury done to the lead casing when it was being drawn into the duct. Such injury is usually due to the roughness of the walls, and the cement which has seeped through the joint and formed cutting edges after hardening. Cable troubles are also due to stray currents leaking through the joints, as a result of improper installation and the impossibility of securing proper alignment. These objections, however, are eliminated by the use of fiber conduit, which has a smooth interior and water-tight joints. Unlike that made with tile conduit, the connection made with fiber conduit is ideal, affording perfect alignment, and does not require the use of mandrels or dowel-pins, cement, mortar or burlap at the joints. It is also true that fiber conduit is impervious to moisture, gases, acids, and other corrosive elements; thus, water, gas, and stray currents cannot reach the cable protected by this material. It is a good non-conductor, doing away entirely with the trouble caused by stray currents, and it is also an absolute preventive of electrolysis, which destroys many cables, gas and water pipes each year.

Control and instrument wiring and field and exciter circuits are invariably run in iron conduit; first, because they are so numerous and their directions varied; and second, because, being small, they require protection against mechanical injury. The cheapest and least conspicuous place to install them is in the concrete floors.

The practice of choosing a conduit having an inside diameter at least 30 per cent greater than the outside diameter of the cable will give good results; Table LIII also gives the size of conduit recommended for different sizes of conductors. All conductors of cables for duct service should be stranded, to facilitate installation.

In laying out a conduit job, the size and number of the wires required should first be ascertained; then the sizes of conduit should be found from Table LIII. One-half inch is usually used for branch conduits and is the smallest size permitted by the National Electric Code. In running several conduits together, a pull-box will be found more economical than elbows for making turns, as one pull-box will take the

TABLE LIII

CONDUIT SIZES FOR DIFFERENT SIZE WIRES

No. B. & S.	Circular Mils.	Amperes, Rubber.	Size of Pipe.			Circular Mils.	Amperes, Rubber.	Size of Pipe.		
			1-Wire.	2-Wire.	3-Wire.			1-Wire.	2-Wire.	3-Wire.
18	1,020	3	½	½	½	500,000	390	2	2	4
16	2,583	6	½	½	½	550,000	420	2	4	4
14	4,107	12	½	½	¾	600,000	450	2	4	4
12	6,530	17	½	¾	¾	650,000	475	2		
10	10,380	24	½	¾	1	700,000	500	2		
8	16,510	33	½	1	1	750,000	525	2		
6	26,250	46	¾	1	1¼	800,000	550	2		
5	33,100	54	¾	1¼	1¼	850,000	575	2½		
4	41,740	65	¾	1¼	1½	900,000	600	2½		
3	52,630	76	¾	1¼	1½	950,000	625	2½		
2	66,370	90	¾	1½	2	1,000,000	650	2½		
1	83,690	107	1	1½	2	1,100,000	690	2½		
0	105,500	127	1	2	2	1,200,000	730	2½		
2.0	133,100	150	1	2	2	1,300,000	770	2½		
3.0	167,800	177	1¼	2	2½	1,400,000	810	3		
4.0	211,600	210	1¼	2	2½	1,500,000	850	3		
	200,000	200	1¼	2	2½	1,600,000	890	3		
	250,000	235	1½	2½	2½	1,700,000	930	3		
	300,000	270	1½	2½	3	1,800,000	970	3		
	350,000	300	1½	2½	3	1,900,000	1010	3		
	400,000	330	1½	3	3	2,000,000	1050	3		
	450,000	380	2	3	4					

place of several elbows. Wires should not be pulled through conduits with a block and tackle, as this will not only injure the insulation, but wedge the wires in such shape that they cannot be removed readily if desired. The end should be reamed out carefully when conduit is cut, as the bur may otherwise cut through the insulation. Conduits should be securely fastened to walls and ceiling by use of pipe straps or hooks. All exposed ends of conduit in new buildings should be plugged to prevent plaster and dirt from falling into them.

Single vs. Multiple Conductors. Low-voltage cables for direct-current service, such as exciter and field leads, are as a rule of the single-conductor type. This, however, does not refer to control and instrument wiring, for which multi-conductors with as many as a dozen conductors are used. These are as a rule of different-colored braids so as to facilitate identification during installation.

Whether single- or multiple-conductor cables should be used for the alternating main conductors depends on the size, length of run,

and whether they are lead-covered or not. When lead covering on cables is required, multiple-conductor cables are always preferable, since the eddy currents in the lead sheaths of the single-conductor cables increase the energy loss. In fact, single-conductor, lead-covered cables should not be used in large sizes on alternating-current circuits without careful consideration.

With high-voltage, single-conductor, lead-covered cables, static discharges may take place through the insulation to the lead, rapidly injuring the insulation, and a breakdown soon follows. If the cable is not lead-covered a static discharge may take place to the duct, and this also has a tendency to break down the insulation in time. In multiple-conductor cables this action does not occur, the static activity being neutralized.

Single-conductor cables are made in sizes up to 2,000,000 C.M. and three-conductor cables up to 600,000 C.M.

General Practice. The following is a general summary of prevailing practice covering the kind of conductors and the manner in which they are installed in a station.

Bare Grounded Conductors. Bars, tubing, cable, wire: Used for all kinds of ground connections or ground return circuits.

Bare Conductors on Insulators. Bars, tubing, wire: Generally employed for circuits above 13,200 volts.

Insulated Conductors on Insulators. Wire, cable, rods: Used for all circuits up to 13,200 volts when not housed in compartments or conduits.

Insulated Conductors in Iron Conduit. Cable: Employed for voltages up to 1200 volts, generally for small-capacity circuits where size of conduit does not exceed 2 inches.

Insulated Conductors in Clay or Fiber Ducts. Cable: May be used for large capacity circuits for voltages up to 13,000, provided ducts are maintained free from moisture.

Leaded Conductors in Ducts or Conduits. Cable: Used for voltages up to 13,200 when ducts or conduits are subject to moisture.

For convenience of reference, station wiring may also be classified as follows:

1. Exciter and field wiring.
2. A.C. generator and low-tension transformer wiring.
3. Control and instrument wiring.
4. High-tension wiring.

Exciter and Field Wiring. These leads consist, as a rule, of single-conductor rubber-covered cables with a double weatherproof braid (or tape and braid), although for sizes larger than No. 0000 B. & S. the insulation may be varnished cambric. Because of the inductive dis-

charge in field circuits, causing an excessive rise in potential when opening the circuit, it is important that a liberal margin of safety be allowed in the insulation. For damp locations lead-covered cables may be required. These leads are mostly installed in iron conduits.

Generator and Transformer Wiring. For this wiring varnished cambric insulation is preferable, as previously stated, the thickness of the insulation varying with the generator voltage. For absolutely dry locations a good weatherproof braid may well serve as a mechanical protection against abrasion, but the ducts should nevertheless be provided with drains so that the cables will under no circumstances lay in water which may be accumulated from condensation. For damp localities, lead-covered cables should always be used, and to be on the safe side the use of such cables is always to be recommended. End-bells are always required for such cables.

Exposed main wiring is generally considered out of date; if it is used, the cables should be well supported and guarded and perfectly covered with a fireproof covering to prevent a fire from spreading from one circuit to another. The installation of the cables in ducts or conduits is much to be preferred. For very large capacity units, bus-construction can often be used to advantage.

Fiber ducts should be used for all alternating-current cables, although iron conduit is permissible if all conductors of one circuit are run in the same conduit. With single-conductor, lead-covered cables, and preferably also for multi-conductor, fiber conduits should be used.

Whether single- or three-conductor cables are to be used depends on the size, the length of run and the loss in the lead sheath. Single-conductor cables are made, as stated before, in much larger sizes than three-conductor, and have, of course, a greater radiating capacity; but on the other hand, especially for long runs, it is found that three-conductor cables will be more economical, especially for lead-covered cables. This is evident when one considers that three lead sheaths will be required as compared to one, even though each of the three will be somewhat smaller than the single one. On the other hand, the eddy-current losses in the lead sheath for a single-conductor cable are not negligible, while with a multi-conductor cable they are entirely neutralized. Lead sheaths are, as a rule, grounded at one end to get rid of accumulation of static electricity, and a ground of the lead sheath at the other end of the cable can very easily occur without being noticed, resulting, with single-conductor cables, in circulating currents in the lead sheath. These currents are only limited by the resistance of the lead, and the losses caused thereby may be quite considerable. Of course, where the size is such that two or more conductors per phase

are required, it is possible to " nest " the conductors so as to neutralize the inductive effects.

In selecting cables for generator leads, a larger factor of safety should be allowed than for ordinary cable practice. Since such leads are not usually protected by any automatic circuit breakers, it is good practice to select a cable for this purpose with an insulation thickness 50 per cent greater than the normal working voltage of the generator.

Control and Instrument Wiring. Under this class would be grouped the control circuits for oil switches, rheostat and governor motors, etc., secondaries of current and potential transformers and all other similar conductors. These conductors are always of a very flexible, rubber-covered, weatherproof, multi-conductor type, installed in iron conduit. Occasionally, where the location is very damp, a lead covering may be desirable. It is possible to pull this cable through a conduit some 100 feet in length with four standard conduit bends in the run.

The best practice is to lay the conduits in the floor and let them terminate as near the switchboard sill as convenient. Frequently the ends of the conduits are bent to point upwards and cut to extend just a short distance above the finished floor. This often necessitates a number of visible crossings of the leads where the conduits cannot be run to the desired point. To obtain a neater construction, a pull-box with cover can be provided in the floor along the back of the board, and the conduits arranged so as to terminate in the walls of the box. Provision is then made for bringing the leads from this box to the desired point at the bottom of the board, the necessary splices and crossings being made in the box.

High-tension Wiring. For circuits above 13,200 volts, bare conductors are generally used, because of the increased cost of ordinary insulation for such high voltages, and because such conductors are necessarily spaced far apart and generally located at a considerable distance from the floor. They are, therefore, rigidly mounted on insulators and carefully guarded.

Size of Cables. (Current-carrying Capacity.) For the comparatively short runs encountered in power stations, the size of the conductors is generally governed by the permissible current-carrying capacity and this, in turn, is determined within practical limits by the maximum temperature which the insulation surrounding it will withstand. First, the temperature must not be high enough to cause too rapid a rate of deterioration of the insulation. The maximum temperature is, roughly, 85° C. for saturated paper, 75° C. for cambric, and 60° C. for rubber. Second, the temperature must not be high enough to decrease the puncturing resistance of the insulation below safe limits.

This temperature varies with the normal working E.M.F. of the circuit. Based on these two considerations, it is recommended that the maximum operating temperatures of the conductors of insulated cables be limited to the values given below:

Heating and Temperature of Cables (*Standardization Rules of the A.I.E.E.*). The maximum safe limiting temperature in degrees C. at the surface of the conductor in a cable shall be:

For impregnated paper insulation (85-E);

For varnished cambric insulation (75-E);

For rubber compound insulation (60-0.25E);

where E represents the effective operating E.M.F. in kilovolts between conductors.

Thus, at a working pressure of 6.6 Kv., the maximum safe limiting temperature at the surface of the conductor or conductors in a cable would be:

For impregnated paper insulation	78.4° C.
For varnished cambric insulation	68.4° C.
For rubber compound insulation	58.35° C.

The actual maximum safe continuous-current load for any given cable is determined primarily by the temperature of the surrounding medium and the rate of radiation. This current value is greater with direct than with alternating-currents, and decreases with increasing frequency, being less for a frequency of 60 cycles than for 25 cycles. This difference in carrying capacity for direct- and alternating-current is of slight practical importance for conductors less than 500,000 cir. mils in area, at commercial frequencies, i.e., 25 and 60 cycles.

Furthermore, owing to the fact that alternating-current flowing in large cables has greater density on the surface of the conductor than in the center, so-called skin effect, an ordinary cable will not carry as many amperes alternating-current with the same temperature rise as it will direct-current. To overcome this, it has in the past been common practice on single-conductor cables, 700,000 cir. mils and larger for 60 cycles and 1,000,000 cir. mils and larger for 25 cycles, to make up the cable in annular form, using a non-conducting core (usually fiber), and stranding the copper wires around this. The annular form thus increases the carrying capacity by utilizing more of the copper, and there is a further increase in the capacity due to the larger radiating surface. In view of the fact that the rope core cable has a greater carrying capacity, due to its increased radiating surface, it could advantageously be adopted for all cables, direct-current or alternating-current for sizes 700,000 cir. mils and above.

It is apparent from the above that the carrying capacity of a cable depends on so many factors that no table can be given which applies to all conditions, and considerable care should be exercised in selecting the size if it is necessary to economize. Tables LIV and LV will, however, serve as a guide for determining the safe current-carrying capacity under three assumed conditions, X, Y, and Z. Condition X is such as to require the maximum-size cable, while condition Z is the most favorable, requiring the minimum size.

The use of these tables is best illustrated by a couple of examples:

Assume that it is desired to find the safe size of a single-conductor, varnished cambric, insulated cable, installed in duct, the operating

TABLE LIV

Current-Carrying Capacity of Cables

(Continuous Rated Apparatus)

Maximum Ampere Capacity Permissible.	Condition *Z*.	Condition *Y*.	Condition *X*.
25	#10	#9	#8
35	# 8	#8	#6
50	# 6	#6	#4
70	# 6	#4	#2
110	# 4	#2	1/0
130	# 2	1/0	2/0
175	1/0	2/0	4/0
225	2/0	4/0	300,000
290	4/0	300,000	400,000
360	300,000	400,000	500,000
450	400,000	500,000	600,000
550	500,000	600,000	750,000
675	600,000	750,000	1,000,000
775	750,000	1,000,000	1,250,000
900	1,000,000	1,250,000	1,500,000
1075	1,250,000	1,500,000	2,000,000
Cables in Multiple			
1300	2—1,500,000	1—2,000,000	1—1,250,000
1500	1—2,000,000	2—1,250,000	2—1,500,000
1750	2—1,250,000	2—1,250,000	2—1,500,000
2100	2—1,250,000	2—1,500,000	2—2,000,000
2600	2—1,500,000	2—2,000,000	4—1,250,000
3100	2—2,000,000	4—1,250,000	4—1,500,000
4200	4—1,250,000	4—1,500,000	4—2,000,000
5200	4—1,500,000	4—2,000,000	6—1,500,000
6200	4—2,000,000	6—1,500,000	6—2,000,000

voltage being 6600 volts and the continuous current to be carried 1000 amperes.

Referring to the first column in Table LIV, we must use the next higher current value, or 1075, and it is seen that the cable may have a size from 1,250,000 C.M. to 2,000,000 C.M., depending on the operating condition. Then, going to Table LV, we find in the eighth line from the top (corresponding to our case) that two conditions, Y and X, are given, the former being limited to a 1,000,000 C.M. cable and the latter to a 2,000,000 C.M. By comparing the results from the two tables it is apparent at once that the Z condition is out of the question entirely, and, furthermore, that the Y condition, corresponding to 1,500,000 C.M., also gives too small a value, as this condition was limited to a 1,000,000 C.M. cable. The size must, therefore, correspond to condition X, or 2,000,000 C.M.

As another example, assume that a 750-volt varnished cambric, insulated cable in conduit is to carry 175 amperes. What size is required?

Referring again to Table LIV, we have three different sizes to choose from, 4/0, 2/0 and 1/0. From Table LV, sixth line from the top, we see that this case also involves all three operating conditions and that the limit of the Z condition is a 4/0 cable, so that it will be safe to use a 1/0 cable for our case.

Suppose, on the other hand, that the current to be carried had been 675 amperes. This would have come within the limit of the γ condition and the required size of the cable would be 750,000 C.M.

Single-conductor lead-covered cables above 600,000 C.M., 25 cycles and 3/0, 60 cycles, should only be used after special consideration is given to the lead-sheath current; and multiplied single-conductor cables on 60-cycle circuits should be suitably arranged to eliminate initial induction and thus balance the reactance and apportion the current carried in each conductor.

For secondary instrument current wiring, where the watts loss in the secondary leads must be kept within certain limits, so as to deduct as little as possible from the permissible instrument load on the transformer, it is the recommended practice to make runs up to 75 feet of 19/25 multi-conductor cable, corresponding in conductivity to a No. 12 B. & S. wire. For runs of from 75 to 150 feet, 19/22 cable, corresponding in conductivity to No. 10 B. & S. wire, should be used for mechanical reasons as well as for increased conductivity. For potential and control wiring, 19/25 cable may be used in practically all instances. The above distances refer to 110-volt circuits, and for 220 volts they can, of course, be doubled. In general, the size of control leads must

TABLE LV

Classification of Conditions X, Y and Z

		To 4/0 Inclusive.	To 500,000 C.M. Inclusive.	To 1,000,000 C.M. Inclusive.	To 2,000,000 C.M. Inclusive.
Single Conductor:					
In free air:					
V.C. and paper	Up to 750 V.	Z	Z	Z	Z
	3,500 V.	Z	Y	Y	Y
	7,500 V.	Y	Y	Y	Y
	15,000 V.	Y	Y	Y	Y
Rubber	750 V.	Y	Y	Y	Y
In ducts:					
V.C. and paper	750 V.	Z	Y	Y	X
	3,500 V.	Y	Y	Y	X
	7,500 V.	Y	Y	Y	X
	15,000 V.	Y	Y	Y	X
Rubber	750 V.	Y	Y	X	X
Three Conductor:					
In free air:					
V.C. or paper	750 V.	Y	Y		
	3,500 V.	Y	Y		
	7,500 V.	Y	Y		
	15,000 V.	Y	Y		
Rubber	750 V.	X	X		
In ducts:					
V.C. or paper	750 V.	Y	X		
	3,500 V.	Y	X		
	7,500 V.	Y	X		
	15,000 V.	Y	X		
Rubber	750 V.	Y	X		

also be determined from the standpoint of voltage drop, the permissible drop depending on the minimum voltage required for the apparatus in question. This is generally stipulated by the manufacturers.

TABLE LVI

Size and Ampere Capacity of Copper Tubing

Maximum Continuous Ampere Capacity.	Outside Diameter, Inches.	Inside Diameter, Inches.
150	$\frac{3}{4}$	$\frac{11}{16}$
300	$\frac{15}{16}$	0.776
500	$1\frac{5}{16}$	1.084

Instrument transformer secondaries should be permanently grounded. Where secondaries cannot be grounded at any point, as for instance in the case of instruments and meters which have secondary current and primary potential coils, the secondary wiring must be insulated and installed to safely withstand primary potential. One common ground bus, not less than No. 4 B. & S., should be run across the back of the switchboard, and apparatus intended for grounding should be mounted on the switchboard and connected to this ground bus. The switchboard pipe framework, except when insulated, should be connected to this ground bus, one connection being made for every three pipe joints in series.

Steel work supporting high-potential switching equipment should be carefully grounded at several points so as to prevent the possibility of high voltage occurring between sections of the steel work. No ground connection for this service should be of less than No. 6 B. & S. flexible cable.

For open high-tension wiring utilizing bare conductors, the size depends on the current to be carried as well as the heat-radiating conditions. For very large alternating currents, such as those in low-tension busbars of large size, the skin-effect may be appreciable, requiring a low current density. As a rule, this may vary anywhere from as low as 300 to 400 amperes per square inch to 1500 amperes per square inch, depending on the conditions. This is dealt with more fully under the section on "Busbars," page 597.

For very high-voltage work using copper tubing, the sizes given in Table LVI are quite common.

Corona Limit of Voltage. In determining the size of high-tension conductors, attention must also be given to the possibility of the formation of corona. Table LVII gives the highest safe three-phase voltage for any given size of wire. The values are based on sea level, but may be corrected for other altitudes by the correction factors given in Table LVIII.

Economic Considerations. In determining the size of a conductor, the economic side of the problem should not be lost sight of, although it may not be of such great importance for the station wiring as for the distribution or transmission system. The most economical area is that for which the annual outlay equals the annual cost of the energy loss, and according to this rule, the cheaper the power, the less should be the capital outlay for the conductors, thus allowing a smaller size to be used and a correspondingly increased loss. In general, the cost of ducts, insulators and supports may be considered as not affected by the variation in size, the outlay being assumed to be affected only by the comparative cost of the cable itself.

Voltage Drop. In a continuous-current circuit, the drop at the terminals of a circuit with resistance R and traversed by a current I ampere, is $I \times R$ volts. Likewise, in an alternating-current circuit, the drop in voltage of a circuit with an impedance Z, traversed by a current of I effective amperes, is $I \times Z$ volts.

The voltage drop in alternating current circuits, therefore, depends on both the resistance and reactance, but with wires close together, as in conduit work, the reactance will generally be small. The drop should be calculated for the given power factor, load, and corresponding current, and the following approximate formula may be used.

$$\text{Volts drop per wire} = IR \cos \phi + IX \sin \phi,$$

where I = current per wire in amperes;
R = resistance in ohms per wire;
X = reactance in ohms per wire;
$\cos \phi$ = power factor of load.

Volts drop of two-phase circuit $= 2 \times$ (volts drop per wire).
Volts drop of three-phase circuit $= 1.73 \times$ (volts drop per wire).

Resistance as well as reactance values for single-conductor cables are given in Table LIX. The values are for 2000 feet of wire, i.e., for each wire of a circuit of that length, and apply equally well to bare or lead-covered cables, as the insulation or lead covering has practically no effect on the self-induction.

Table LX gives reactance and impedance values for 1 mile three-conductor cables. Unlike the reactance values given in Table LIX, which were single-phase, these values are three-phase; i.e., by multiplying them by the current, the drop in the full-line voltage (not voltage to neutral) is obtained directly. In calculating the values, a 2 per cent allowance for spiral of strands and a 2 per cent allowance for spiral of conductors has been made. All the results are based on a cable 1 mile long, but can, of course, be obtained for any shorter distance by reducing the figures given in direct proportion. Similarly, the values correspond to a frequency of 60 cycles. For any other frequency, the values given must be multiplied by that frequency and the result divided by 60.

TABLE LVII

Corona Limit of Voltage

Kilovolts between Lines Three-phase Cables

SEA LEVEL

Size B. & S. or Cm.	Diameter in Inches.	Spacing Feet.					
		8	10	12	14	16	20
0	0.374	95	98	102	104	106	109
00	0.420	104	108	111	114	117	121
000	0.470	114	118	121	124	127	132
0000	0.530	125	130	135	138	141	146
250,000	0.590	138	144	149	152	156	161
300,000	0.620	.....	151	156	161	165	171
350,000	0.679	.....	161	166	170	175	180
400,000	0.728	.....	171	176	180	185	192
450,000	0.770	.....	178	184	190	194	200
500,000	0.818	.....	188	194	199	205	210
800,000	1.034	.....	.....	234	241	244	256

To find the voltage at any altitude, multiply the voltage found above by the δ corresponding to the altitude, as given in Table LVIII.

For single-phase or two-phase, find the three-phase volts above and multiply by 1.16.

TABLE LVIII

Altitude Correction Factor δ

Altitude, Feet.	δ	Altitude, Feet.	δ
0	1.00	5,000	0.82
500	0.98	6,000	0.79
1000	0.96	7,000	0.77
1500	0.94	8,000	0.74
2000	0.92	9,000	0.71
2500	0.91	10,000	0.68
3000	0.89	12,000	0.63
4000	0.86	14,000	0.58

TABLE LIX

Reactances and Resistances of Single-conductor Cables

(By H. W. Fisher, A.I.E.E., 1905)

Size of Conductor. in B. & S. Gauge.	Diameter in Inches.	Resistance in ohms per 2000 Feet of Wire at 68° Fahr.	Reactance in Ohms per 2000 Feet of Wire at a Frequency of 60 Cycles per Second. Distances between Centers of Conductors in Inches.													
			½	1	2	3	4	5	6	8	12	18	24	36	48	60
Solid 10	0.1018	1.994	0.116	0.148	0.1803	0.199	0.212	0.223	0.231	0.244	0.2626	0.281	0.294	0.313	0.326	0.337
8	0.1285	1.254	0.107	0.138	0.1695	0.189	0.202	0.212	0.220	0.233	0.2519	0.271	0.284	0.302	0.315	0.326
6	0.1620	0.7888	0.095	0.127	0.1589	0.178	0.191	0.201	0.209	0.222	0.2412	0.260	0.273	0.292	0.305	0.315
4	0.2043	0.4960	0.085	0.117	0.1482	0.167	0.180	0.190	0.198	0.211	0.2305	0.249	0.262	0.281	0.294	0.305
Strand 4	0.232	0.4960	0.078	0.111	0.1424	0.161	0.174	0.185	0.193	0.206	0.2247	0.244	0.257	0.275	0.288	0.299
3	0.260	0.3934	0.072	0.105	0.1372	0.155	0.168	0.178	0.186	0.199	0.2195	0.237	0.250	0.269	0.282	0.293
2	0.292	0.3120	0.067	0.099	0.1318	0.150	0.163	0.173	0.181	0.194	0.2142	0.232	0.245	0.264	0.277	0.288
1	0.328	0.2474	0.063	0.095	0.1264	0.145	0.158	0.169	0.177	0.190	0.2088	0.228	0.241	0.259	0.273	0.283
0	0.373	0.1962	0.056	0.089	0.1205	0.139	0.152	0.163	0.171	0.184	0.2029	0.222	0.235	0.253	0.267	0.277
00	0.418	0.1556	0.052	0.084	0.1153	0.134	0.147	0.158	0.166	0.179	0.1977	0.216	0.230	0.248	0.262	0.272
000	0.470	0.1234	0.046	0.078	0.1099	0.129	0.142	0.152	0.160	0.173	0.1923	0.211	0.224	0.242	0.255	0.265
0000	0.528	0.09786	....	0.073	0.1046	0.123	0.136	0.147	0.155	0.168	0.1869	0.206	0.219	0.237	0.251	0.261
Cir. Mils. 300,000	0.630	0.06902	....	0.064	0.0964	0.115	0.128	0.138	0.146	0.160	0.1788	0.197	0.210	0.229	0.242	0.253
400,000	0.728	0.05178	....	0.058	0.0898	0.109	0.122	0.133	0.141	0.154	0.1722	0.192	0.205	0.224	0.237	0.247
500,000	0.815	0.04042	....	0.053	0.0846	0.101	0.117	0.127	0.135	0.148	0.1670	0.186	0.199	0.218	0.231	0.241
600,000	0.893	0.23452	....	0.048	0.0804	0.099	0.112	0.123	0.131	0.144	0.1628	0.181	0.195	0.213	0.226	0.236
700,000	0.964	0.09258	....	0.045	0.0769	0.096	0.109	0.120	0.128	0.141	0.1593	0.178	0.192	0.210	0.223	0.233
800,000	1.031	0.02598	....	....	0.0738	0.093	0.106	0.116	0.124	0.138	0.1562	0.175	0.188	0.207	0.220	0.230
900,000	1.093	0.02300	....	....	0.0911	0.090	0.103	0.113	0.121	0.135	0.1535	0.173	0.186	0.205	0.218	0.228
1,000,000	1.152	0.02070	....	....	0.0687	0.087	0.100	0.111	0.119	0.132	0.1511	0.170	0.183	0.201	0.215	0.225
1,250,000	1.289	0.01657	....	....	0.0635	0.083	0.096	0.106	0.114	0.127	0.1459	0.164	0.178	0.197	0.211	0.221
1,500,000	1.412	0.01381	....	....	0.0594	0.079	0.092	0.102	0.110	0.123	0.1417	0.160	0.174	0.193	0.206	0.216
1,750,000	1.526	0.01183	....	....	0.0558	0.075	0.088	0.098	0.106	0.120	0.1382	0.157	0.170	0.189	0.202	0.212
2,000,000	1.631	0.01035	....	....	0.0527	0.072	0.085	0.095	0.103	0.116	0.1351	0.154	0.167	0.185	0.199	0.209

A	1.05	1.10	1.15	1.20	1.25	1.30	1.35	1.40	1.45	1.50	1.60	1.70	1.80	1.90	2.00
B	0.0022	0.0044	0.0064	0.0084	0.0103	0.0121	0.0138	0.0155	0.0171	0.0186	0.0216	0.0244	0.0270	0.0295	0.0319

For any other frequency f, the reactances given in the table must be multiplied by $\frac{f}{60}$.

The reactances for diameters of conductors which lie between the sizes given can be found by direct interpolation.

The reactance for any distance D not given in the table can be found as follows: let d = the nearest smaller distance in the table. Divide D by d and taking a value of A nearest to the quotient find the corresponding value of B, which must be added to the reactance corresponding to the size of conductor and distance d.

TABLE LX

Approximate Reactance and Impedance of Three Conductor Cables per Mile
60 Cycles

Size.	Thickness of Insulation. 2/32 by 2/32 In. A	2/32 by 2/32 In. B	3/32 by 3/32 In. A	3/32 by 3/32 In. B	4/32 by 4/32 In. A	4/32 by 4/32 In. B
6	0.307	3.843	0.345	3.845	0.379	3.848
4	0.288	2.423	0.323	2.427	0.351	2.431
2	0.272	1.546	0.302	1.552	0.328	1.557
1	0.264	1.232	0.292	1.238	0.315	1.244
1/0	0.260	0.988	0.282	0.993	0.304	1.000
2/0	0.253	0.798	0.276	0.806	0.297	0.815
3/0	0.247	0.648	0.268	0.656	0.287	0.665
4/0	0.243	0.519	0.263	0.544	0.279	0.553
250,000	0.239	0.470	0.257	0.478	0.273	0.488
300,000	0.236	0.410	0.252	0.421	0.267	0.430
350,000	0.233	0.370	0.248	0.380	0.262	0.390
400,000	0.231	0.342	0.246	0.352	0.259	0.361
450,000	0.229	0.320	0.243	0.330	0.256	0.340
500,000	0.228	0.304	0.241	0.314	0.254	0.325

Size.	Thickness of Insulation. 5/32 by 5/32 In. A	5/32 by 5/32 In. B	13/64 by 13/64 A	13/64 by 13/64 B	8/32 by 8/32 In. A	8/32 by 8/32 In. B
6	0.407	3.852	0.443	3.855	0.473	3.860
4	0.376	2.435	0.410	2.440	0.439	2.446
2	0.351	1.562	0.381	1.570	0.407	1.576
1	0.337	1.250	0.365	1.258	0.390	1.265
1/0	0.325	1.006	0.352	1.013	0.375	1.023
2/0	0.315	0.822	0.340	0.830	0.360	0.840
3/0	0.304	0.673	0.328	0.685	0.350	0.695
4/0	0.295	0.561	0.317	0.572	0.338	0.585
250,000	0.288	0.496	0.310	0.510	0.330	0.522
300,000	0.281	0.438	0.301	0.452	0.320	0.465
350,000	0.276	0.396	0.296	0.413	0.313	0.426
400,000	0.272	0.371	0.291	0.384	0.308	0.398
450,000	0.268	0.349	0.287	0.364	0.301	0.375
500,000	0.266	0.334	0.283	0.348	0.298	0.360

A—The three-phase reactance of a cable 1 mile long.

B—The three-phase impedance of a cable 1 mile long.

Note.—Of the two figures given for the insulation—for example 5/32 by 5/32—one is the insulation thickness around each conductor and the other the thickness of the insulation belt around the three conductors. The former only is of importance as far as the reactance value is concerned as it determines the distance between the conductors.

CHAPTER IX

ECONOMIC ASPECTS

PRELIMINARY CONSIDERATIONS

Like every other commercial undertaking, the promotion of a hydro-electric development involves a very careful preliminary investigation. Upon this investigation will largely be based the success attained in securing financial support for the enterprise. Such investigations should be considered from the engineering, as well as the commercial side, and the man to whom this important task is entrusted should have a sound and conservative judgment in analyzing such proportions.

This applies to small developments as well as large ones. It may even apply with more force to the smaller plant, because an error which would be of minor importance in a large plant may involve serious financial consequences in a small one.

No two streams offer quite the same problem of power development, and a multitude of conditions must, therefore, be investigated in every case. These involve a complete and most efficient study of the watershed, rainfall and hydrographic data, for determining the available stream-flow and the storage possibilities. Estimates of the probable market for the power must also be made; and the type and size of the development must be so planned that the total annual cost of delivering the necessary power, including fixed charges, will not exceed the amount the available customers can afford to pay, the rates generally being governed by the cost of competing power generated from fuel.

The location of the development should be such that it will insure the most economical results. Usually this condition is realized when the maximum head is utilized, but consideration must also be given to the land which may be overflowed by so increasing the head. A study of the watershed may, furthermore, show that several developments of a smaller size will give better economy than one large plant, and will serve the entire system in such a way that the power from the new developments will form a more economical addition to that which may already be supplied by other plants; in other words, that the load factor will be

such as to improve the load factor of the other plants and of the system in general.

As a rule, it seldom pays to develop a stream for the maximum stream-flow, and it is always necessary to decide how much more than the minimum stream-flow should be counted upon. This also involves the problem of providing for water storage, if such is feasible, or for auxiliary steam power.

The cost estimates should be made with the greatest care, and no amount of work or experiment should be considered excessive, if it will serve to make certain the ground upon which the estimates are made. After having estimated liberally for all known requirements, it is well to provide, in addition, a substantial sum of money, and so arrange the finances that if, contrary to expectations, the estimates should be exceeded, sufficient funds will remain in the treasury for completing the development. Nothing is so discouraging, and in many cases so disastrous, as a reorganization of the undertaking at its very beginning.

Every feature of the proposition should, of course, be investigated from the legal point of view. This involves the real estate flowage rights, rights of way, rights of occupying public highways, etc. Such matters must be carefully adjusted at the beginning.

A very complete general guide for the compilation of water power reports and field data has been prepared by Mr. J. T. Johnston, Hydraulic Engineer of the Water Power Department of the Dominion of Canada, and is contained in its 1914 Annual Report. This guide is so complete and useful that it is reprinted in the following in full.

GENERAL GUIDE FOR THE COMPILATION OF WATER POWER REPORTS AND THE SECURING OF FIELD DATA [1]

The increasing number of inspections and field investigations on the part of the field engineers of the Dominion Water Power Branch, has rendered desirable the preparation of a uniform guide upon which may be based the various reports forwarded to head office, in order that, so far as possible, their form may be standardized.

It is also considered that a guide of this description can be used to advantage by the engineer when making his field investigations into the projects under examination. A careful study in the field outlined herein, will, as a rule, prevent the overlooking of important data which should be secured on the ground.

[1] From the 1914 Annual Report, Dominion Water Power Branch, Department of Interior, Canada.

The guide is, therefore, submitted for a dual purpose; first, for use as a framework for the standardization of the test of power reports submitted by field engineers, and second, for use by engineers while in the field as a general memorandum of the various features calling for attention and field study.

Field investigations vary in character, the majority dealing with the following conditions: (1) Applications for water-power privileges, such applications being unaccompanied by detailed data as to the site of stream. (2) Applications for water-power privileges accompanied by fairly well-developed plans, setting out the general scheme of development. (3) First-hand investigation of entirely new sites or series of sites, for the purpose of studying power, storage and conservation features.

In preparing the following instructions, the above has been kept in view, and the outline hereunder is intended to serve as a general guide, only such portions being utilized as are directly applicable to the class of report under preparation. It is not intended that these instructions should limit a report solely to the ground covered herein; much must be left to the discretion of the engineer in charge of the investigations. The points briefly dealt with represent, however, the general important features which require investigation and discussion, in order that the ground may be completely covered.

Summary of Principal Divisions

A brief summary of the sections and subheadings follows: Further details of the ground to be covered under each section are given later.

I. *Sources of data used in report.*
- (1) Why investigated and scope of investigation.
- (2) Personal examination—route followed and time consumed.
- (3) Run-off records from departmental stream measurement offices.
- (4) Maps.
- (5) Existing reports.
- (6) Miscellaneous.

II. *Summary of report.*

III. *General introductory.*

Description, including location as to province, river, cities, township, range and section.

IV. *Water Supply.*

(1) General description of drainage area.

(2) Actual records if available, showing maximum, minimum, and mean discharge for each month, also absolute minimum for year. Measurements on ground if foregoing are not available.

(3) Rainfall, temperature, evaporation.

(4) Storage already developed and effect of same.

(5) Storage possibilities—

(*a*) Location of reservoir site or sites.

(*b*) Height of dam and class of dam suitable.

(*c*) Capacity of reservoirs and extent of adjacent drainage basin.

(6) Prior water rights above and below power site—water supply, irrigation or power.

(7) Ice conditions, during winter months and in spring flood (frazil, anchor and floating ice).

(*a*) Under present conditions on river.

(*b*) After construction of plant.

(*c*) Without storage.

(*d*) With storage.

V. *Description of existing Power Development on the River.*

VI. *Detailed Work at Site investigated.*

(1) Scope of the inspection at the site.

(2) Accessibility of site and transportation problems.

(3) Detailed information and plans of site—

(*a*) Contour plan of site.

(*b*) Cross-section.

(*c*) Profiles.

(4) Foundation conditions.

(5) Flooding and pondage.

(6) Existing interests.

VII. *Possible Power Developed.*

(1) Horse-power at wheel shaft without storage—

(*a*) At minimum flow.

(*b*) For the nine high months.

(2) Horse-power at wheel shaft with storage. Discuss utilization of local pondage at site for peak loads.

VIII. *Estimates.*

Cost of power developed—capital and annual.

Cost of storage—capital and annual.

IX. *Market for Power.*
- (1) Present.
- (2) Future.
- (3) Length of transmission lines, etc.

X. *Suggestions and Recommendations.*

XI. *Appendices.*
- (1) Plans pertinent to the actual sites investigated.
- (2) Photographs.
- (3) Run-off records.
- (4) Gauge records.
- (5) Reports.
- (6) Maps and plans of existing power plants and structures, etc.

Details as to the Foregoing Sections

I. *Sources of Data used in Report*

This section should set out the basis and authority on which the investigation was instituted, outline the scope of the same, and the organization by means of which the field data were obtained.

It is also intended to summarize the sources of information upon which the subject matter of the report is founded, and to set out in full the degree of thoroughness with which the investigation has been carried on.

II. *Summary of Report*

All the essential features of the report should be brought together here, in a brief statement forming a concise summary of the whole, tabulation of results being made where possible.

III. *General Introductory*

This section should cover the general features of the situation being investigated. This involves a general description of the river and its characteristics, and of the basin as a whole, touching on drainage area, source, direction, drop, falls, rapids, banks, river bed, tributaries, lakes, muskegs, swamps, forest, cultivation along banks, settlements, glaciers, general topographical and geological features, etc., and giving the definite location of the site under study.

IV. *Water Supply*

(1) *General Description of Drainage Area.*—Under general description of the drainage area those features should be dealt with which are of direct importance to the question of the water supply, such as probability of sudden floods, influence of the seasons, etc.

(2) *Run-off Records.*—If the site inspected is situated on one of the rivers covered by any of the systematic stream measurement work carried on by the department, the existing records should be utilized as a basis upon which the run-off may be discussed. A summary of the essential features of the discharge covering high, low and mean flow, etc., should be inserted, while the records in their complete form should be attached as appendices in Section XI of the report. Where no records have been taken on the river, estimates or measurements of the flow at the time of the inspection should be made, either by meter or by whatever method of stream measurement is most applicable or convenient. From this, in conjunction with high-water marks in evidence, and from the testimony of local inhabitants as to extreme low- and high-water conditions, and from a study of the run-off conditions of streams in the vicinity, as careful an estimate as is possible should be made of the extreme low- and high-water conditions on the river, also of the average low and high flows which may be expected. With these data, the months and seasons in which the above conditions are usually in evidence, must be given.

(3) *Rainfall, Temperature and Evaporation.*—The maximum, minimum and mean annual rainfall as recorded at the nearest stations maintained by the Meteorological Service should be discussed, being utilized in estimating the run-off if stream-flow records are not to hand. Temperature and evaporation records, if available, should also be fully considered.

(4) *Storage Already Developed.*—If storage is already in operation in the river basin above the site, a full discussion of the same is required under the heads of location; owners and operators; date of installation; area and volume of reservoir and of tributary drainage basin; description and condition of dam and structures; effect on natural run-off conditions, actual experience since being placed in operation covering date, time of filling and emptying reservoir; gauge records if available (to be attached in full in appendix); method of control; photographs, comments, etc., etc. Copies of plans of structures are to be secured if possible.

(5) *Storage Possibilities.*—The question of storage possibilities and locations on the upper waters should be covered as thoroughly as the

conditions of the inspection, and the detailed instructions issued therewith, may require. If a visit is made to any lakes in the upper basins, the general elevation of the banks of the same relative to the water service should be recorded, with notes as to what flooding would result if the lakes were raised to various definite limits. When the reservoir is in a surveyed district the approximate land flooded should be given in sections and quarter sections.

At the outlets all the conditions affecting the construction of a dam, and the type of structure advisable, are required. This will include foundation conditions; height and character of banks; a section across the river at the point selected for the dam carried sufficiently far up the banks to cover all possible limits to which it may be advisable to hold the lake surface.

A profile should be secured of the water surface from the lake outlet to the dam site. Should there be a possibility of securing storage by means of dredging or otherwise clearing the outlet, a profile should be obtained of the water surface, and, if possible, of the river bed from the lake to a sufficient distance below the dam site; any other field information necessary to determine what is involved in the construction of a dam and in the operation of a storage reservoir is also required.

When circumstances render it inadvisable to visit the upper waters of the basin for the purpose of personal inspection, a review of the storage situation, as far as it can be gathered from existing maps and from local information, should be included.

The surface area and capacity of all storage reservoirs considered, together with the area of the drainage basins adjacent to the same and their sufficiency to fill the reservoirs, should be fully covered; the beneficial effect of such storage on the flow of the river should be discussed.

(6) *Prior Water Rights.*—Any existing or projected schemes of municipal water supply, irrigation or water power, which have diverted or may in the future permanently divert a portion of that river flow, thus reducing the water available at the site, should be investigated and reported on.

(7) *Ice Conditions.*—The general conditions in winter along the river as a whole, covering time of freeze up, conditions in midwinter, and time and manner of break up in the spring, should be secured from whatever local sources may be available, or, if possible, from personal observation. The question of anchor and frazil ice under present conditions should be considered carefully, also that of ice jams in the spring, both above and below the site. The possible formation of ice jams below the site and the consequent effect on the tail-water and floor elevation of the powerhouse, should be particularly noted.

The frazil and anchor-ice conditions, to be anticipated at the site after the construction of the plant, should be discussed. In this connection a careful study covering the winter conditions and troubles experienced in the operation of any existing plants on the river, together with methods of remedying the same, is advisable.

The probable effects on ice conditions of the development of storage for the purpose of increasing the winter flow, should also be covered.

V. *Description of Existing Power Plants*

Existing power developments along the river should be dealt with under the following general heads: Ownership of plant and when constructed; description of layout and structures (dam, intake, penstocks, tunnels, canal, forebay, power-house, foundations, transmission, substations, etc.), and present conditions of the same; head at different seasons; installation (electrical and hydraulic machinery in detail); auxiliary power, power-load and power factor, daily load curves if possible, use of power, market for power, present and future; special features, etc., comments and photographs. Plans of plant to be secured if possible and attached to appendix.

VI. *Detailed Work at Site Investigated*

(1) *Scope of the Inspection at the Site.*—If a definite and well-defined project be investigated, the engineer making the inspection should study the general scheme carefully in the light of his personal inspection of the ground, and should record his opinion as to the engineering and economic feasibility of the same, pointing out whatever weaknesses may be apparent, and recommending whatever changes in design, layout or scheme of development he may consider advisable.

When no definite scheme of development has been proposed, the inspecting engineer is expected to outline the most feasible scheme which his study on the ground may suggest, setting out the head available and method of securing the same. He should also gather all information and field data which may be essential to its proper consideration and to getting out the estimates. A layout of his scheme, together with all pertinent data, should be plotted on the contour plan of the site.

Arrangements should be made on the ground for the installation and continued reading of gauges at all points where the record of the same is advisable.

Numerous photographs illustrating the site are required.

(2) *Accessibility of Site.*—Secure all data with reference to accessibility of the site. This includes the distance to the nearest railway

line; the ease or difficulty of building a spur line to the site should the size of the development warrant it; the condition of any roads in the vicinity and their suitability for heavy transport; the length of new road that may be required; the use which can be made of water transportation as a means of access. In brief, the best means of connecting the site with existing lines of traffic, should be covered.

(3) *Detailed Information and Plans at Site.*—(*a*) *Contour Plan.*—Enough rough instrument work must be done to permit of plotting a fairly accurate contour plan of the whole vicinity covered by the proposed layout. These contours should extend above the highest elevation to which there is any possibility of raising the head-waters of the proposed plant. Sufficient notes should be taken to plot on the said plan, with the elevations, any rock outcrops which may be in evidence. Should the rock outcrop along both banks of the river, the continuous line of demarcation between the rock and the overlying material should be plotted, *with the elevations*, along both shore lines. The plan should also indicate all other classes of material, such as clay, gravel, sand, loam, etc., which may be in evidence, together with notes as to whether the site is wooded, cleared or cultivated, etc.

Water levels (together with date of taking, and river-flow, if possible) should be recorded and plotted on this plan at all important points, such as the brink and foot of falls and rapids, marking the limits of the still water above and below. All eddies and back waters should be marked and the elevation and date recorded. The general line of the brink and foot of any falls which will be involved in a proposed scheme of development should be secured and tied in to the plan. The high- and low-water levels to be expected in the tail-water of the projected power station are of particular importance. Maximum high-water marks along the shore should be carefully noted.

All natural features of which advantage might be taken in laying out a power-plant should be fully shown on the plans and discussed in the report.

(*b*) *Cross-section.*—A cross-section of the river bed and both banks along the line of the proposed dam, and sections of any alternative sites which may present themselves to the engineer on the ground, should be secured and plotted. Sections when plotted should indicate the character of the ground surface and river bed and of foundation conditions, either in evidence or assumed, throughout.

(*c*) *Profiles.*—A profile of the river surface from the upstream limit of the new pond created by the plant is desirable, but is not essential should the circumstances of the inspection render the securing of the same inadvisable. In all cases, however, a profile of the river surface

and, if possible, of the river bed, from a point up stream from the dam, to below the tail-race of the power-plant is required. A profile section through the dam, intake, headrace (or pipeline, as the case may be), power-plant, and tail-race, showing such governing elevations as, head-water, crest of dam, floor of generator room, tail-water, etc., should also be obtained in the best manner which circumstances may dictate.

Profiles of any pipe or canal lines are also required.

(4) *Foundation Conditions.*—Full note should be made of the natural conditions of the ground and river bed at the proposed dam and power-house site. If there is rock in sight a full statement of its character, weathering qualities, etc., is required. If no rock is in evidence, as careful an investigation of the existing conditions as circumstances permit is required.

(5) *Flooding and Pondage.*—The direct flooding which will be caused by the construction of the proposed or any feasible plant at the site should be determined approximately either by inspection or if necessary by rough instrument work. If the land has been surveyed the flooded portion can be listed by sections and quarter sections.

The utilization of this local pondage in connection with peak loads at the project plant should receive general consideration.

(6) *Existing Interests.*—All existing interests, such as bridges, trails, roads, railways, buildings, etc., that may be affected by the construction of the plant and by the consequent flooding, should be fully reported on. The question of the logging and fishing interests on the river should be discussed in considerable detail.

VII. *Possible Power Developed*

The question of power possible of development should be discussed from the standpoints of, first, no storage available, and second, storage available. Under the first head the power available at minimum flow and the power which might be developed during the eight or nine months not included in the extreme low-water season should be covered.

Under both headings the beneficial utilization of the local pondage for peak loads and the consequent increased power output should be dealt with.

VIII. *Estimates*

Approximate estimates of the capital and annual operating costs of the proposed scheme of development and the basis on which these are made should accompany the report, together with similar estimates of the cost of any proposed storage reservoirs.

IX. *Market for Power*

This will involve as thorough an investigation as the circumstances warrant of the present and future power market in the surrounding municipalities and district. Possibilities for the local use of power at the site and in the immediate vicinity are also to be covered. With the question of power market, the question of distance of transmission necessary to reach the same requires careful consideration.

X. *Suggestions and Recommendations*

Suggestions, comments or recommendations with reference to the foregoing and the writer's opinion as to the questions at issue should be set out in full. The location of suitable metering stations for the continuous record of the river-flow at vital points should be covered in these recommendations. The question of sources of power other than water, in the vicinity, and their possible more economic development is, at times, most important. All recommendations should be set out definitely and concisely.

XI. *Appendices*

(1) *Plans.*—(*a*) A general plan (a section of published map is desirable) showing the location of the power and storage sites with reference to centers of population. (*b*) A general plan (a section of published map) showing the whole drainage basin above the power site, together with storage reservoirs. (*c*) Contour plans of the sites of power plants and storage dams. (*d*) Cross-sections along dam sites. (*e*) Profiles of reach of river affected and of pipe and canal lines. (*f*) Any other plans warranted by the nature of the investigation.

All plans, sections, and profiles, etc., should be suitably numbered, and should be referred to in the text by these numbers whenever necessary. A complete list of the above plans, giving numbers and description, should be included in the table of contents of the report.

(2) *Photographs.*—A set of all the views taken to illustrate the different features of the report should be mounted and included. Where these views deal with power-plant and storage-dam layouts, they should be accompanied by a sketch plan showing the point from which each is taken and the direction the camera faced. The films should be numbered, dated and titled, in order that all prints may be immediately recognized. A complete list of the photographs, giving numbers, date and subject should be included in the table of contents of the report.

(3) *Run-off Records.*—All tabulated records and plotted curves which may have been secured.

(4) *Gauge Records.*—Copies of all gauge records which are of interest in connection with the power or storage features of the report.

(5) *Reports.*—Copies of any existing reports which may have been made with reference to power development on the river.

(6) *Maps.*—Any maps which may usefully illustrate the report, and any plans which may have been obtained covering existing power-plants, storage works, bridges, etc., etc.

Investigation and Inspection of a Series of Sites

Frequently the investigation of a river involves the consideration and detailed inspection of a series of power sites. In such cases, the report covering the work should follow the foregoing guide, with the following slight changes.

It will be noted in the foregoing, that Sections I to V can be applied as they stand, to the compilation of a report on a series of sites. Sections VI to VIII are directly applicable to each individual site; Section IX is applicable to individual sites or to groups as conditions may warrant, and Sections X and XI are applicable as they stand to the ending up of the report. In preparing a report on a series of sites, the only alteration advised in the foregoing guide is that under Section VI, each site is treated as a unit and completely covered according to the outline in Sections VI to IX. The new Sections VII and VIII will correspond to X and XI in the foregoing synopsis.

Following is the outline for a report covering a series of investigated sites, with the necessary alterations:

I. *Sources of Data Used in Report.*

(1) Why investigated and scope of investigation.
(2) Personal examination, route followed and time consumed.
(3) Run-off records from departmental stream measurement offices.
(4) Maps.
(5) Existing reports.
(6) Miscellaneous.

II. *Summary of Report.*

Concise statement of results of investigations covering all essential features of the report. Tabulation of results as to power and storage.

III. *General Introductory.*

Description, including location as to province, river, cities, township, range and section.

IV. *Water Supply.*

(1) General description of drainage area.

(2) Actual record, if available, showing maximum, minimum and mean discharge for each month, also absolute minimum for year. Measurements on ground if foregoing are not available.

(3) Rainfall, temperature, evaporation.

(4) Storage already developed and effect of same.

(5) Storage possibilities.

(*a*) Location of reservoir site or sites.

(*b*) Height of dam and class of dam suitable.

(*c*) Capacity of reservoirs and extent of adjacent drainage basin.

(6) Prior water rights above and below power site; water supply, irrigation or power.

(7) Ice conditions during winter months and in spring flood (frazil, anchor and floating ice).

(*a*) Under present conditions on river.

(*b*) After construction of plant.

(*c*) Without storage.

(*d*) With storage.

V. *Description of Existing Power Developments on the River.*

VI. *Sites Investigated.*

(*a*) *Detailed work at each site investigated.*

(1) Scope of the inspection at the site.

(2) Accessibility of site and transportation problems.

(3) Detailed information and plans at site,—

(*a*) Contour plan of site.

(*b*) Cross-sections.

(*c*) Profiles.

(4) Foundation conditions.

(5) Flooding and pondage.

(6) Existing interests.

(*b*) *Possible Power Developed.*

(1) Horse-power at wheel shaft without storage,—

(*a*) At minimum flow.

(*b*) For the nine high months.

(2) Horse-power at wheel shaft with storage. Discuss utilization of local pondage at site for peak loads.

(*c*) *Estimates.*

Cost of power developed, capital and annual.
Cost of storage, capital and annual.

(*d*) *Market for Power.*

(1) Present.
(2) Future.
(3) Length of transmission lines, etc.

(*e*) *Recapitulation.*

Comprehensive discussion of the foregoing data as to the individual sites, and a consideration of the same as a whole or in groups, as local conditions may warrant.

VII. *Suggestions and Recommendations.*

VIII. *Appendices.*

(1) Plans pertinent to the actual sites investigated.
(2) Photographs.
(3) Run-off records.
(4) Gauge records.
(5) Reports.
(6) Maps and plans of existing power plants and structures, etc.

The details of the data to be covered in each section are in the main as previously outlined in connection with the report on an individual site. A careful study of these details is desirable.

In Section VI each site investigated should be completely covered under the headings, *a*, *b*, and *c*, before discussion on a second site is commenced. The market for power under the heading *d* should be discussed with each individual site or with groups of sites, as general conditions may warrant. Plans and photographs should be suitably numbered in order that they can be referred to, when necessary, in the text.

Attached as appendices to this Guide are reproductions of the loose-leaf forms, R–11 to R–22, used in the field by the engineers of the Water Power Branch. The great flexibility of the loose-leaf system is claimed to be of outstanding advantage to the rapid and efficient carrying on of the survey work, more especially on those investigations where the results have been plotted into final shape in the field. The loose leaves generally lend themselves most readily to a simple filing system in which the records of the survey are properly grouped, and are at all time available for ready reference.

R-11.

DIARY OF..

WATER POWER BRANCH, DEPT. OF THE INTERIOR,

OTTAWA

..........Day of........................19.....

..........Day of........................19.....

..........Day of........................19.....

R-12 Return to Valuable

WATER POWER BRANCH, DEPT. OF THE INTERIOR, OTTAWA

Location.................... File No............ Page No......

.... Instrument Man................................191..

Object.	Plus.	Ht. Inst.	Minus.	Elevation.	Remarks.

R–13 Return to Valuable

WATER POWER BRANCH, DEPT. OF THE INTERIOR, OTTAWA

Location.......................... File No.......................... Page No.....

........................Instrument Man..............................19.....

Object.	Azimuth.	Magnetic.	Stadia.	Distance.	V. Angle.	Hor.	Vert.	Elevation.

R–14 Return to Valuable

WATER POWER BRANCH, DEPT. OF THE INTERIOR, OTTAWA

Location.................. File No.................. Page No.....

........................Instrument........................Man........................19......

Object.	+	H. I.	−	Elev.	Three Wires.	Dist.	Bearing.

R–15 Return to Valuable

WATER POWER BRANCH, DEPT. OF THE INTERIOR, OTTAWA

Location.............................. File No.............................. Page No.........

.............................Instrument Man..............................191.....

STATION.	AZIMUTH.	MAGNETIC.	ANGLE.	REMARKS.

R–16 Return to Valuable

WATER POWER BRANCH, DEPT. OF THE INTERIOR, OTTAWA

LEVEL NOTES

Stream..

Locality..

Party.......................... Date...................19.....

Station.	B. S.	Ht. Inst.	F. S.	Elevation.	Remarks.
....	....	....	....	....	....
....	....	....	....	....	....
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No.......of......Sheets......Comp. by............Chk. by...........

Form R-17—Front

R-17. Return to

WATER POWER BRANCH, DEPARTMENT OF INTERIOR, OTTAWA

DESCRIPTION OF RIVER STATION

On.................................. {Creek / River} at.....................

near.........................Post Office, Prov. of.....................

Established..............191...., by................................

Name of observer.......................P. O. address..............

pay $...... occupation........distance......time of daily observation....

Location of station with respect to towns, bridges, highways, railroads, tributaries, islands, falls, dams, etc..

....

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Description and location of the gauge, also relative to the measuring station. If chain gauge, give length from end of weight to the marker......

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Description of the equipment from which measurements are made......

....

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Location and description of initial point for soundings.................

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FORM R-17—BACK

Channel above the station: straight or curved for about........ feet, water swift, sluggish, etc...

....

Channel below the station: straight or curved for about........, feet water swift, sluggish, etc..

....

Right bank: high, rocky or low, liable to overflow, clean or wooded, etc.

....

....

Left bank: high, rocky or low, liable to overflow, clean or wooded, etc.

....

....

Bed of the stream: rocky, gravel, sandy, clean or vegetation, shifting

....

Number of channels at low and high water, approximate depth of water, etc...

....

Note any condition which may affect the measurement, etc............

....

....

Bench marks: Describe fully, give elevation above zero of the gauge and above sea level or other datum, if possible; make sketch bringing out the principal features...

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Take sufficient soundings to develop a cross-section of stream bed and, by use of level, develop banks to above high-water mark. Refer all elevations to gauge datum.

Make a sketch plan on cross-section paper, showing the relative location of the station, gauge bench marks, tributaries, towns, etc.

FORM R-18—FRONT

R-18 ○ Return to ○ Valuable

WATER POWER BRANCH

DEPT. OF INTERIOR, OTTAWA

Current Meter Notes—Ice Cover

Date.................19.........A.M. P.M. Stream.............................

Party.............................Locality.............................

Meter No.......Gauge height, beg..........end.........mean..............

Total area.............Mean velocity.............Discharge..............

Observations.						Computations.						
	Thickness Ice.	Depth under Ice.				Velocity.						
Distance from Initial Point.	W. S. to Top Ice.	Of Water.	Of Observation.	Time in Seconds.	Revolutions.	At Point.	Mean in Vertical.	Mean in Section.	Area.	Mean Depth.	Width.	Discharge.
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No......of......Sheets, Comp. by......Chk. by......Make notes on back

FORM R–18—BACK

Weights used..

Wind...

Method of supervision of meter (single wire or cable)......................

Stay wire used or not used...

Point of measurement with reference to gauge (i.e., distance above or below)

....

Length of gauge chain checked and found to be....ft. and corrected to.... ft.

Condition of gauge and equipment at river station..........................

....

Repairs necessary..

....

REMARKS:...

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FORM R-19—FRONT

R-19 Return to Valuable

Water Power ◯ Branch, Department of the Interior ◯ Ottawa

Current Meter Notes

Date....................191.....A.M./P.M. Stream...........................

Party............................Locality...............................

Meter No.......Gauge height, beg.......end......mean................

Total area............Mean velocity............Discharge..........

Observations.					Computations.						
					Velocity.						
Distance from Initial Point.	Depth.	Depth of Observat.	Time in Seconds.	Revolutions.	At Point.	Mean in Vertical.	Mean in Section.	Area.	Mean depth.	Width.	Discharge.
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No......of.....Sheets, Comp. by......Chk. by.......Make notes on back

FORM R-19—BACK

Weights used. . . . .

Measurements by reading, from cable, bridge or boat. . . . .

Wind. . . . .

Method of supervision of meter (single wire or cable). . . . .

Stay wire used or not used. . . . .

Point of measurement with reference to gauge (is distant above or below). . .

Length of gauge chain checked and found to be. . . .ft. and corrected to. . . .ft.

Condition of gauge and equipment at station. . . . .

Repairs necessary. . . . .

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REMARKS:. . . . .

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R–20 Return to

WATER POWER BRANCH, DEPT. OF THE INTERIOR, OTTAWA

Survey.......................... File No.......................... Page No.....

Location..........................

Photographer.......................... ....191....

Roll Holder.	Film.	Time.	Exposure.	Stop.	Date.	Notes.	File No.

R–21

DEPARTMENT OF THE INTERIOR, OTTAWA

WATER POWER BRANCH

DISCHARGE MEASUREMENT NOTES

Date................., 191.. No. of Meas. ....

..............................River at.................................

Width........Area........Mean Vel.........Cor. M. G. H.............

Party............................Disch................................

Gauge, checked with level and found....................................

Measurement began at............Measurement ended at................

First reading of gauge......ft. at......	Date rated....................
Gauge......ft. at sta........ft. at......	Method of meas................
Gauge......ft. at sta.......ft. at......	No. meas. pts.......Coef.......
Gauge......ft. at sta.......ft. at......	Av. width sec.......Av. depth..
Last reading of gauge.......ft. at......	G. Ht. change (rate per hr.).....

Meter No.............................% error by........rating table..

Meas. from cable, bridge, boat, wading; Meas. at......ft. above, below gauge

If not at regular section note location and conditions.....................

Method of suspension......Stay wire......Approx. dist. to W. S..........

Arrangements of weights and meter; top hole........; middle hole........;

bottom hole...

Gauge inspected, found..........; Cable inspected, found................

Distance apart of measuring points verified with steel tape and found.......

Wind..........upstr., downstr., across. Angle of current................

Observer seen and book inspected...

Examine station locality and report any abnormal conditions which might change relation of G. Ht. to disch., e.g., change of control; ice or debris on control; back water from; condition of station equipment................

Sheet No. 1 of..........sheets. If insufficient space, use back of sheet.

R-22

Return to

WATER POWER BRANCH, DEPARTMENT OF INTERIOR, OTTAWA

GAUGE RECORD

Station No..........

..............................River at..............................

OLD GAUGE

Location..

....

....

Zero..............................191......Elev..................

Kind of gauge..............................Length..................

NEW GAUGE

Location..

....

....

....

Established..............................191....by..................

Zero..............................191....Elev..................

Kind of gauge..

Reading from..............................ft. to..................

Gauge reader..............................Address..................

Time of observation..

Reason for change..

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Remarks..

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Engineer

AMOUNT OF ENERGY AVAILABLE

The two principal factors which enter into the determination of the available energy of a stream are the fall or head and the quantity of water flowing.

The head is usually limited by the cost of the overflowed lands, and the fall may be either naturally concentrated at one point in a cascade or it may be artificially concentrated, for the purpose of development, by combining the fall of several cascades or a series of rapids. This may be accomplished by either of two methods: first, by building a dam at the downstream end of the rapids to impound the water, so that the entire fall is concentrated at the dam; or, second, by building a dam at the upstream end of the rapids and conducting the water through a closed pipe to the lower end of the rapids, where the resulting head and pressure will be exactly the same as in the first instance. A variation in the latter method consists in diverting the water from the natural channel at the head of the rapids and carrying it to a canal or flume, on a slight down grade, along the side of a hill to a suitable point, and there erecting a forebay from which the water is turned into penstocks which run directly down the slope to the stream, where the power-house may be located. The latter method, involving the construction of an open canal or flume, is open to the objection that trouble may be experienced from the accumulation of ice in the winter time. The first two methods described are the most common.

The second quantity to be determined is the water flowing in the stream per unit of time, usually expressed in cubic feet per second, but for low-head developments the two factors of head- and stream-flow are, as a rule, inseparable, as the head fluctuates considerably with the different stages of the stream.

To be of value, the stream-flow data should extend over a period of several years (fifteen to twenty) in order that the minimum as well as the maximum flows which may be expected, and their duration, may be known. While the average flow characteristics are of interest, they are not of very great value.

The United States Geological Survey and various States have been taking and recording stream-flow measurements in a systematic manner, for many years; and data are now available for streams in nearly all sections of the country. There are, however, a large number of streams, especially the smaller ones, where few, if any, discharge measurements have been made. In such cases it is necessary to base estimates of discharge on the records at other stations in the same precipitation belt and watershed, and data of other systems of similar nature may also

be used. Rainfall data are useful as a check on flow estimates, and they also show years of high and low water, but care should be exercised in their use.

The daily and seasonal distribution of stream-flow is best shown graphically in the hydrographic curves, as fully explained under the section on Stream Flow. By comparing a number of such hydrographs, the dryest year, i.e., the year with the minimum flow, can readily be ascertained.

For convenience in making a scientific analysis and study, the stream-flows, instead of being arranged chronologically as in the hydrographs, may be arranged according to magnitude, as in Fig. 425. The

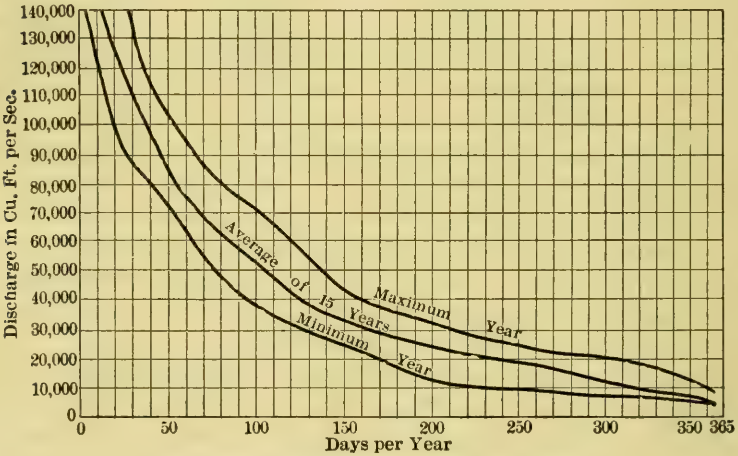

FIG. 425.—Stream-flow Duration Curves.

discharge is plotted as ordinate, and the corresponding number of days during which the respective discharge has occurred as abscissas. The time may also be given in percentage of the entire year, instead of in days, and horse-power values may be substituted for the discharge by making allowance for any possible variation in the head at the different discharges.

POWER DEMAND

The market for electric power is most widely distributed and will always continue to grow with the growth of the community in which it is located. Furthermore a hydro-electric development frequently creates its own market, by inducing a number of industries to locate in its immediate vicinity, as at Niagara Falls.

The possibility of finding a market for the power which is to be developed, and the price at which this power may be disposed of, are two of the first questions to be investigated. This investigation involves a close canvass of the present power consumption for both public and private use, the character of the power demand, as to periods of day and season, present and future competition, present rates, and the cost at which power can locally be generated from fuel. From these investigations it is possible to arrive at a fairly close estimate of the required capacity, load factor and value of the service, and future considerations should be based thereon. In the absence of the above information, a fairly close estimate of the revenue may be made by comparing the possibilities of the community to be served with those of similar places already developed.

A typical power market has three main divisions, namely, lighting, manufacturing, and traction. If the greatest demand from each source came at a different time from that of the others, the total demand would be so distributed as greatly to reduce the required maximum capacity of the power plant. As a matter of fact, however, the demand from no one of these sources is uniform, and, furthermore, there is more or less overlapping of these demands. The demand for manufacturing purposes is very nearly uniform and, except for a few industries and in exceptional cases, falls between 7 o'clock in the morning and 7 o'clock in the evening. Practically all the demand for lighting is at night, chiefly in the evening. The period of traction demand is longer than that for either manufacturing or lighting, and embraces practically the entire periods of both.

The period of lowest combined demand is normally between the hours of midnight and 4 o'clock in the morning. Traction demand begins in earnest about 6 o'clock and is immediately followed by the manufacturing demand. The forenoon period of active demand is from 6 o'clock to noon. In the middle of the day manufacturing establishments cease operations for an hour or less and resume again about 1 o'clock, thus restoring the demand to the level of the forenoon. Between 4 o'clock in the afternoon and 7 o'clock in the evening there is a distinct overlapping of the three demands. It is during these hours, especially in winter, that practically all the lights are turned on, manufacturing concerns have not yet stopped for the day, and street cars are carrying, perhaps, their heaviest loads. It is during this period that the highest demand of the twenty-four hours is reached.

There is also a seasonal fluctuation in a typical power market. The demand in winter is usually greater than in summer, and the daily fluctuation is likewise greater. The increased demand grows out of

the increased requirements for lighting and, in some cases, for traction. The greater fluctuation is mainly due to the fact that between the hours of 4 o'clock in the afternoon and 8 o'clock in the evening more power is required for light in winter than in summer.

LOAD AND DIVERSITY FACTOR

The load factor of a plant or system is the ratio of the average to the maximum power during a certain period of time. The average load may thus be taken over a period of one year, one month or one day, while the maximum load must necessarily be limited to very short periods, depending on the overload capacity of the water wheel or the generator. In other words, it is the ratio of the actual station output to the maximum possible output with continuous service.

It is also a measure of the extent to which the necessary total investment is being utilized, as a plant with yearly load factor of 50 per cent is turning out just double the energy of another plant of the same maximum load and with a load factor of 25 per cent. This means that, while the fixed charges of both plants are the same, the gross income of the plant with 50 per cent load factor should be nearly twice as great as that of the other. The importance of a good load factor is thus apparent, and everything that will improve this factor should be sought.

The nature of the load, as measured by the load factor, forms necessarily also a very important element in determining the value of water power as compared to steam power. For load factors below 50 per cent, the former often turns out to be the cheaper; but as the load factor increases above this value, water power may show up to the better advantage. This is evident from the fact that the cost of hydroelectric power is made up chiefly by the fixed charges and is very little dependent on the operating charges and the amount of power used.

Electricity is applied to an enormous variety of uses, the yearly load factors of which also vary widely, as shown in Table LXI.

The yearly load factor for any class of service is determined largely by the seasons, the habits of the people, and other conditions which ordinarily do not change very materially. Improvement in the load factor must, therefore, be obtained largely by combining different classes of service, the maximum demands of which occur at different times of the day or of the year. Also, the larger the number of customers in any class the better will be the load factor.

A recognition of the importance of the diversity factor has undoubtedly the most marked effect in increasing the load factor and thereby the economy of production. This factor is the ratio between the sum

TABLE LXI

Load Factors

SMALL AND MEDIUM LIGHTING CUSTOMERS

	Per Cent.
Buildings, public	17.6
Churches	12.4
Clubs	9.6
Flats	6.9
Halls (public)	6.9
Hotels	24.4
Offices (business)	9.2
Offices (professional)	6.7
Residences	7.8
Restaurants	23.4
Shops (bakery)	13.1
Shops (tailor)	8.4
Schools	7.2
Stores (dry goods)	8.2
Stores (cigar)	16.8
Stores (drug)	19.3
Stores (grocery)	10.3

LARGER POWER AND LIGHTING CUSTOMERS

	Per Cent.
Bakeries	12
Blacksmith shops	15
Breweries	45
Boots and shoes	25
Bottling works	10
Candy manufacturing	18
Clothing manufacturing	15
Department stores	30
Furniture manufacturing	28
Foundries	15
Ice cream manufacturing	20
Ice making	30
Laundries	20
Machine shops	20
Newspapers	18
Packing houses	30
Railroad depots	50
Tanneries	20
Textile mills	20

of the maximum demands of various classes of service and the actual simultaneous maximum demand, and the more non-coincident these peak services are, the greater will be this factor.

The chief means of improving the load factor has been the addition of industrial load. In the early days of electric lighting companies, the load factors were very low, because of the absence of day load.

FIG. 426.—Typical Daily Load Curve for Large City Service.

To-day, many central stations sell far more energy for power than for light, and this is naturally distributed over a longer part of the twenty-four hours. The power load, also, not being simultaneous with the lighting load to any great extent, still further improves the load factor. Residence load has generally been characterized by a poor load factor, but by the use of day-load devices such as flat irons, cooking devices,

fans, heating apparatus, vacuum cleaners, etc., a much improved result is obtained.

The problem of combining electric railway loads and central station loads on one system has received increasing attention in recent years, and in some cities of this country great strides have been made toward effecting such combinations successfully. Figure 426 thus shows a typical load curve for a large city.

There are a number of industries which offer ideal loads for large hydro-electric companies; such as mining, electro-chemical work, irrigation and farming, while much is expected from the railroad field when the time has arrived for the economical electrification of our trunk lines.

Table LXII gives statistics for 1921 on the outputs, peak load, and load factors of a number of the largest generating systems in this country and Canada, and Table LXIII gives the average power used by the leading industrial establishments in the Eastern States covered by the contemplated Super Power Zone, based on the 1919 Census of Manufactures.

PRIMARY AND SECONDARY POWER

Many companies make two classes of contracts for power, known as primary and secondary. Under the terms of a primary power contract, they guarantee to supply the amount of power contracted for continuously throughout the year. It is evident that the maximum amount of such power is limited by the minimum stream-flow and can be safely increased only by providing water storage or steam auxiliaries to augment the shortage during low-water periods.

The minimum flow of the stream to be used may be the absolute minimum, the minimum of the average year, the average minimum, or some other value of low discharge of the stream. The selection of the particular value to be used depends upon the degree of insurance of the continuity of the supply that is justified by the conditions. The added cost of the insurance of the supply should be equated to the losses, direct and indirect, sustained by failure of the supply. If it is planned to secure absolute continuity, in so far as stream-flow is concerned, it will be necessary to use the absolute minimum of the stream and to use it in connection with the maximum load that can occur upon any day when the stream-flow may be lowest. This degree of insurance is seldom necessary; usually it will be sufficient to use the stream-flow which can be depended on for, say four years out of five; in other words, to eliminate the extraordinary low discharge which will occur once in

TABLE LXII

Data on Peak Load, Output and Load Factor of Largest Generating Systems in United States and Canada

(From Electrical World, April 29, 1922)

	1921			
	Peak Load, Kw.	Date of Peak Load.	Yearly Output, Kw.-Hr.	Yearly Load Factor, Per Cent.
Commonwealth Edison Company	525,640	Dec. 21	1,928,271,943	41.8
Niagara Falls Power Company	298,120	Dec. 22	1,855,120,000	71.0
Pacific Gas & Electric Company	265,925	Nov. 29	1,489,088,657	63.9
New York Edison and United Electric Light & Power Company	422,721	Dec. 14	1,475,276,053	39.8
Southern California Edison Company	238,480	Dec. 13	1,224,718,196	58.6
Montreal Light, Heat & Power Consolidated	165,900	Nov. 16	907,231,573	62.4
Detroit Edison Company	201,500	Nov. 23	897,980,200	50.9
Philadelphia Electric Company	213,570	Dec. 8	877,047,595	46.9
Shawinigan Water & Power Company	160,500	Dec. 19	863,124,240	61.4
Ontario Power Company	151,000	Jan. 5	825,115,600	62.3
Public Service Electric Company of New Jersey	213,502	Nov. 28	821,198,975	44.0
Southern Power Company	218,300	Feb. —	790,000,000	41.2
Duquesne Light Company	164,240	Feb. 1	702,897,985	49.0
Toronto Power Company	109,000	Nov. 28	630,468,000	66.1
Mississippi River Power Company	117,450	Nov. 28	602,580,980	58.5
Montana Power Company	116,600	Jan. 11	572,277,989	56.1
Cleveland Electric Illuminating Company	141,850	Dec. 15	564,819,267	45.5
West Penn Power Company	106,919	Dec. 21	516,829,636	55.3
North American Company (Missouri System)	116,275	Dec. 9	508,893,262	49.8
Great Western Power Company	95,540	June 7	490,584,257	58.7
Buffalo General Electric Company	115,000	Nov. 14	479,862,700	47.5
Pennsylvania Power & Light Company	84,203	Sept. 27	442,507,974	53.6
Brooklyn Edison Company	137,800	Dec. 6	438,887,775	36.4
Alabama Power Company	115,500	Dec. 20	432,991,540	42.8
Pennsylvania Water & Power Company	83,000	Nov. —	419,987,000	57.7
Puget Sound Power & Light Company	99,800	Dec. 1	419,197,581	47.9
Consolidated Gas, Electric Light & Power Company of Baltimore	108,330	Nov. 30	415,335,614	43.8
Niagara, Lockport & Ontario Power Company	87,000	Nov. 2	415,153,634	54.5
New England Power Company	112,200	Nov. 9	405,979,457	41.3
Consumers' Power Company	95,410	Dec. 12	397,815,027	47.6
San Joaquin Light & Power Corporation	61,700	June 27	396,174,690	73.3
North American Company (Wisconsin System)	98,887	Nov. 22	375,354,892	43.3
Edison Electric Illuminating Co. of Boston	128,200	Dec. 15	375,025,955	33.3
Washington Water Power Company	70,110	Nov. 23	374,378,300	44.7
Minneapolis General Electric Company	83,590	Dec. 15	373,378,515	50.9
Utah Power & Light Company	75,661	Jan. 8	362,908,000	54.7
Tennessee Power Company	69,100	May 16	342,948,926	56.5
Los Angeles Bureau of Power & Light	51,900	Dec. 21	300,353,806	65.0
Portland Railway Light & Power Company	64,800	Dec. 20	298,514,571	52.6
Georgia Railway & Power Company	72,000	11/3 and 11/28	282,084,977	44.6
Union Gas & Electric Company	75,000	12/14 and 12/23	281,537,273	42.7
Michigan Northern Power Company	35,018	Aug. 14	258,249,673	87.5
Adirondack Power & Light Corporation	61,500	Dec. 21	243,370,354	45.2
Narragansett Electric Lighting Company	72,000	Nov. 23	243,087,000	38.6
Potomac Electric Power Company	65,000	Dec. 14	238,028,571	41.8

TABLE LXII—*Continued*

	1921			
	Peak Load, Kw.	Date of Peak Load.	Yearly Output, Kw.-Hr.	Yearly Load Factor, Per Cent.
Virginia Railway & Power Company	47,000	Dec. 14	208,323,000	50.7
Kansas City Light & Power Company	50,531	Dec. 23	204,752,604	46.3
Great Northern Power Company	44,200	Jan. 5	204,396,860	52.7
Pennsylvania-Ohio Power & Light Company	45,300	Nov. 9	202,670,200	51.0
Southern Sierra Power Co. & Nevada-California Power Co	45,700	6/6 and 8/8	199,452,965	49.9
Idaho Power Company	35,635	Sept. 1	190,215,255	61.0
Northern Ohio Electric Corporation	42,000	Oct. 12	187,249,647	50.9
Rochester Gas & Electric Corporation	48,734	Dec. 16	185,480,692	43.5
Toledo Edison Company	46,700	Dec. 13	179,121,428	43.8
Turners Falls Power & Electric Company	57,900	May 17	170,826,000	33.7
Fort Worth Power & Light Co	29,500	Oct. 15	163,286,500	63.1
Columbus Railway, Power & Light Company	38,440	Dec. 12	160,423,240	47.7
Texas Power & Light Company	33,620	Sept. 22	156,851,213	53.2
Appalachian Power Company	35,600	Dec. 19	154,500,000	49.5
Dayton Power & Light Company	37,500	Nov. 28	134,588,457	41.0
California-Oregon Power Company	20,270	Mar. 16	133,091,607	75.1
Northwest Utilities Company	31,885	April —	132,788,852	47.5
Kansas Gas & Electric Company	25,000	Dec. —	130,479,900	59.6
Nebraska Power Company	28,200	Oct. 28	127,758,800	51.8
Scranton Electric Company	27,900	Dec. 2	117,579,851	48.1
Central Illinois Public Service Company	26,300	Dec. —	114,587,986	49.7
Northwestern Electric Company	22,190	Dec. 12	113,913,335	58.6
Colorado Power Company	25,961	Mar. 9	113,805,044	50.0
Indianapolis Light & Heat Company	29,358	Nov. 9	108,829,278	42.2
Indiana & Michigan Electric Company	28,280	Dec. 16	105,593,490	42.6
Empire District Electric Company	27,700	Dec. —	104,687,540	43.1
Connecticut Light & Power Company	28,255	Nov. 28	101,129,915	40.9
Metropolitan Edison Company	27,900	Nov. 30	99,815,200	40.8
Hartford Electric Light Company	31,700	Nov. 14	97,754,000	39.3
Tacoma Department of Light & Water	28,400	Dec. 20	95,697,600	38.5
New Bedford Gas & Edison Light Company	40,300	Dec. 21	89,857,700	25.4
ELECTRIC RAILWAYS				
Interborough Rapid Transit Company	242,760	Dec. 30	846,487,668	39.8
Brooklyn Rapid Transit Company	116,000	Dec. 22	383,009,325	37.7
Philadelphia Rapid Transit Company	105,303	Dec. 22	333,222,786	36.1
Boston Elevated Railway Company	75,905	Jan. 18	223,061,330	33.5
Pennsylvania R. R. Co., Long Island Power Plant	64,000	Dec. 30	201,922,210	36.0
New York Central Railroad Company	50,750	Dec. 23	149,275,239	33.6
Twin City Rapid Transit Company	44,599	Feb. 8	145,517,164	37.2
Kansas City Railways Company	43,500	Jan. 13	129,804,772	34.0
Western Power Company of Canada	27,200	Mar. 1	122,684,800	51.4

$$\text{Yearly load factor} = \frac{\text{Kw.-hrs. yearly output}}{\text{Kw. peak load} \times 8760}.$$

TABLE LXIII

AVERAGE POWER USED BY INDUSTRIAL ESTABLISHMENTS IN SUPER POWER ZONE
(From Super Power Report)

Industry.		Number of Establishments Using Power.	Average Horsepower per Establishment.
1. Food and kindred products.	a. Slaughtering	552	91
	b. Flour and grist mill products	1,217	48
	c. Bread and bakery products	5,598	11
	d. Sugar refining	13	2,700
	e. All other food products	4,085	44
2. Textiles and their products.	a. Cotton goods, small wares and lace	676	1,320
	b. Knit goods	1,322	68
	c. Silk goods	1,158	120
	d. All woolen goods	623	610
	e. Carpets and rugs	65	490
	f. Dyeing and finishing	565	252
	g. All other fabrics and materials	292	356
	h. Clothing	13,024	6
	i. All other textiles	717	67
3. Iron and steel	a. Blast furnaces	27	6,800
	b. Steel works and rolling mills	112	5,100
	c. Locomotives, not by railroads	5	14,221
	d. All other iron and steel products	6,218	148
4. Lumber	a. Lumber	1,641	46
	b. Furniture and all other	3,069	66
5. Leather	a. Tanned, curried and finished	352	250
	b. Finished products	2,355	38
6. Paper and printing	a. Paper and wood pulp	297	1,620
	b. Manufactures of paper	1,038	54
	c. Printing and publishing	6,956	24
7. Liquors and beverages		1,303	88
8. Chemicals and allied products	a. Coke, excluding gas-house coke	10	3,975
	b. Explosives	23	850
	c. Gas, illuminating and heating	202	540
	d. Petroleum, refining	21	3,167
	e. All other chemicals	1,853	156
9. Stone, clay and glass	a. Cement	28	5,800
	b. All other stone products	1,257	60
	c. All clay products	593	158
	d. All glass products	326	40
10. Metals, non-ferrous	a. Metals, non-ferrous	606	490
	b. Metal products, non-ferrous	2,817	38
11. Tobacco manufactures		567	27
12. Vehicles	a. Automobiles	3,214	18
	b. Cars, not by railroads	11	2,057
	c. All other vehicles	637	23
13. R.R. repair shops	a. Steam railroad repair shops	189	530
	b. Electric railroad repair shops	127	153
14. Miscellaneous industries	a. Metal work	524	116
	b. Rubber goods	217	1,500
	c. Electrical machinery	544	414
	d. Ice manufactured	330	337
	e. Shipbuilding	350	655
	f. All other miscellaneous	5,968	45
15. Laundries		1,563	35
16. Mines and quarries	a. Anthracite coal mines	384	2,340
	b. Mines and quarries, except anthracite coal mines	555	200

every five to ten years. But on this point, as on all others in connection with the matter, the decision depends upon the experience and judgment of the engineer, and no hard-and-fast rule can be laid down. One kind of load demands the highest degree of insurance, whereas loads of a different character may be satisfactorily served with a less degree of insurance.

Secondary power is that amount which is being developed above the primary, and which is only available for a certain time of the year, such as eight or ten months. The continuity of this power is, as a rule, not guaranteed, and the right is reserved to cut off such supply upon reasonable notice. The rates for secondary power are, therefore, much lower than for primary power.

The question of the sale of secondary power has yet not reached the proportions to which it is entitled, but there is every reason to believe that by careful planning of certain industries quite a large amount of secondary power could be very economically utilized.

The extent to which a power site should be developed depends necessarily upon the market conditions for the two classes of service. It needs no argument to prove that where power can be sold at a high price and conditions are favorable, the development can be carried to a higher point of stream-flow than where the opposite conditions prevail. Over-development, however, may entail fixed charges which will make the earning of a surplus only a speculative possibility of the distant future. On the other hand, the present demand and its probable future increase may both be done justice by the correct solution of this factor. As a rule, however, the development of a power site usually also involves the consideration of an auxiliary power source, such as a storage reservoir or a steam plant.

If the secondary power can be sold without an auxiliary steam plant, the amount of secondary power which may be developed economically depends only upon whether or not the price received for such power will cover interest and profit on the investment; that is, the investment which is over and above that for developing primary power. If a steam plant has to be maintained, the amount of secondary power to be developed depends also upon the cost of the steam power.

WATER STORAGE

In the effort to increase the capacity of a hydro-electric plant at times of low water, the question of storage is one of vital importance, and the extent to which the irregular stream-flow can be equalized depends upon the quantity of storage. It is also obvious that no con-

siderable amount of money can be judiciously expended in the construction of storage reservoirs under average conditions unless the head available at the plant is considerable, and this question must be largely determined by local conditions surrounding each individual development.

Water-storage problems are most readily solved graphically by means of "mass-curves," and the most economical solution is fixed by balancing the value in the increase in output as against the cost of

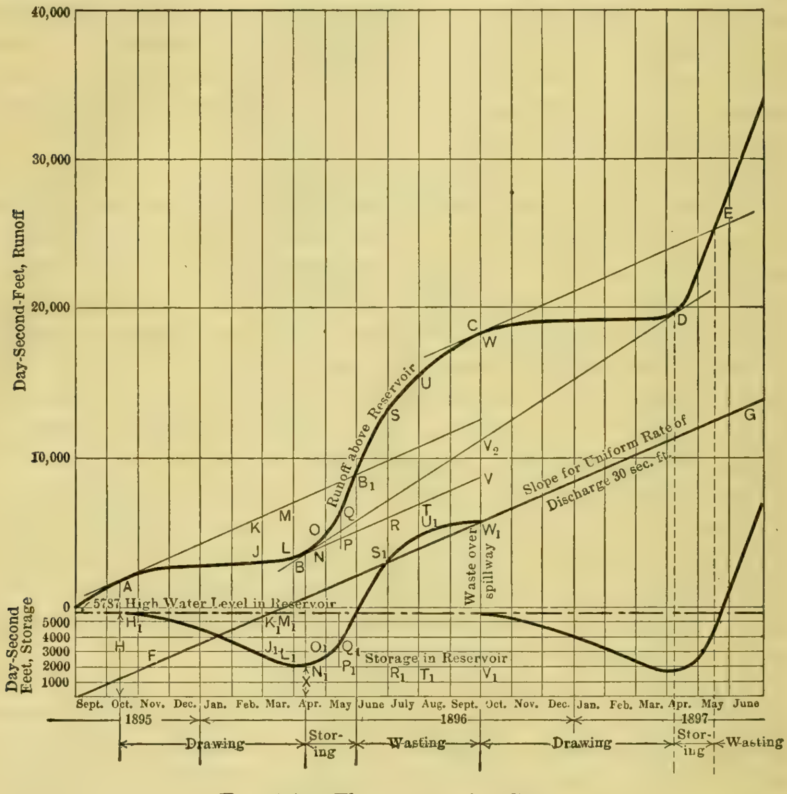

FIG. 427.—Flow-summation Curve.

securing the same. From the mass-curve, the available water for power is obtained and this, under given net heads, will determine the power available.

The application of the "flow-summation" or "mass-curve" to problems of water storage is clearly explained by Mr. E. C. Jansen in the *Engineering News* for December 25, 1913, as follows:

"To plot the stream-flow for any period of time, the mean daily discharges in any convenient unit are added day by day and plotted

as ordinates, the units of time being represented by abscissas, so that the sum total or ordinate on any date represents the total quantity of water which has flowed past the gauging station up to that date (see curve *ABCDE*, Fig. 427). Second-feet (cubic feet per second) are now most commonly used as units of flow and, when the mean daily discharges are expressed as such, the summation of them results in convenient units of day-second-feet or a second-foot flowing for twenty-four hours (1.98 acre-feet) as in Fig. 427. As the length of the ordinates shows the increase or decrease of the twenty-four-hour flow, it will readily be seen that the slope of the curve represents the rate of flow and that a uniform flow is represented by a straight line as *FG*."

The inclination of a tangent to the curve at any point indicates the rate of flow at that particular time, and when the tangent is parallel to the abscissas it illustrates that the flow at that time will just balance the losses caused by evaporation, seepage, etc., while a negative inclination of the curve shows that a loss from the reservoir is taking place.

"Assume, for example, that *FG* represents a regulated or uniform rate of flow of 30 second-feet; then, by applying this slope as a tangent to the summation curve at *C*, it is observed that the stream from about October 1st began to discharge less than this flow and did not rise above the same until the beginning of April at *D*. The flow can be readily interpreted in this way by drawing a datum and different slopes or tangents on a piece of tracing linen and applying this at any point on the curve."

Having a certain reservoir capacity and the mean daily discharges of a stream for a period of years, the method of utilizing the summation curve for finding the maximum regulated flow which can be obtained for power purposes, is explained in the following paragraphs.

"*ABCDE* represents the stream-flow in day-second-feet (usually a period of minimum run-off when water power is contemplated); *FG* is the desired regulated flow and *H* is the capacity of the reservoir in day-second-feet. Starting with a full reservoir on or about October 10, 1895 (the smaller units of time are purposely omitted), the summation curve shows that the stream-flow is below the desired regulated flow AB_1, parallel to *FG*, and that the ordinates *JK*, *LM*, etc., represent the amounts of storage required to maintain the regulation. Plotting these ordinates below the high-water level of the reservoir in the storage diagram as J_1K_1, L_1M_1, etc., the storage curve $H_1J_1L_1$ is obtained, showing the behavior of the reservoir during the uniform rate of discharge for power purposes. At *B*, about April 10, 1896, the summation curve shows that the stream-flow is above the desired regulated flow; consequently, the ordinates *NO*, *PQ*, etc., show the amount of

water which can be stored and these ordinates are plotted as N_1O_1, P_1Q_1, etc., for the remaining portion of the storage curve until the reservoir fills about June 1st. By continuing the plotting of these ordinates RS, TU, etc., as R_1S_1, T_1U_1 etc., in the storage diagram, the curve, $S_1U_1W_1$ is obtained, showing the quantity of water which passes over the reservoir spillway. This process is then repeated, and in this way is ascertained the behavior of the reservoir from year to year while a continuous draft is being made on it. The ordinate X, showing the water left in the reservoir at the end of the drawing period, enables one to experiment with differently regulated flows to ascertain just how much draft the reservoir can stand. Frequently two or three exceptionally dry years in succession in a long period of observation will tax the reservoir capacity to its limit and settle the question conclusively as to the maximum regulated flow obtainable."

Having the mean daily discharges of a stream, it may also be required to find how large a reservoir is required to obtain a maximum regulated flow. This may also be obtained from Fig. 427. By drawing a line from B to D, the maximum regulated flow utilizing all the water is found, and the ordinate V_2W represents the capacity of the reservoir in day-second-feet, which would be required to effect this.

The above method is suitable for determining the power possibilities of a given development when one or two power-houses with accompanying reservoirs are involved. When a large number of related power-houses and reservoirs are involved, this method of using the mass curve of discharge becomes very long and tedious. Also, it is only approximate, giving as a result uniform flow of water, not uniform power, and it fails to take into account regulative effect on the power output of the power-houses situated on the upper sections of the watershed. To solve these more intricate problems, a method of determination has been proposed by Mr. L. A. Whitsit, and is described in the *Engineering News* for September 11, 1913.[1]

The utilization of stored water so as to absolutely insure a fixed minimum flow in all years, while perhaps best for streams whose power is not developed up to the limit, leads to a very uneconomical use of the reservoirs on streams which already are highly developed as to power. As a condition of high ratio of development exists on many streams where storage would be most desirable and valuable, and as this condition will become more and more pronounced on all power streams, it is apparent that the subject of this basis of figuring the power benefits is of importance in securing a proper view of the relation of water storage to water development.

[1] See also Engineering News, Aug. 24, 1916.

The conditions may be such that when the method of regulating for a minimum steady flow of water is applied, the storage capacity is found to have been used to its full extent only once in ten years. During six of the ten years it may not have been used at all, and during two years only about one-half of the capacity may have been used. It is, therefore, evident that capital, if invested for use only once in ten years, must, when it is used, yield a very large return. Such a method of management of a storage reservoir would call forth just criticism when it was discovered that, after money had been spent for the auxiliary power during the low-water season, the storage reservoir remained full of water. This has led the Water Supply Commission of the State of New York to deduce a new method of computation, which is based on an average rate of release of stored waters, so that while the assurance of a certain minimum flow would not be unduly sacrificed, the entire volume of stored water could be used practically every year. This method, which has been termed the "utility" method to distinguish it from the "insurance" method, has been based on a knowledge of the conditions of the larger streams of the State, where the developments can be run at full capacity up to about 60 per cent of the time, reckoned over a long period of time, and it assumes that there is always sufficient demand for power to absorb any additions and render further development after regulation as desirable as before.

Figures 428 and 429 represent graphically the results of an investigation for the regulation of the Genesee River by providing a storage reservoir having a capacity of 13.5 billion cubic feet.

The stream-flows are arranged according to magnitude, and result in the curve marked "Natural Flow of River." Although the vertical scale is given in horse-power, the power is proportional to the stream-flow as long as the head is not affected, and the curve would not be changed in any respect if stream-flow instead of power were used. In order to plot the "Regulated Flow" curve, the mass curve, as previously explained, is used, and the regulated flows are also arranged according to magnitude and the values plotted as for the natural flow.

The results were based on a "present" wheel installation of 29,200 horse-power, and by referring to diagram, Fig. 428, it will be seen that one-fifth of all the water power with regulated flow and present wheel capacity will be derived from the stored water, shown by the vertically sectioned area. Without regulation, the present installation can be operated at its full capacity for only 58 per cent of the time and diminishes to a minimum of about 7500 horse-power. Similarly, the average amount of energy that must be drawn from auxiliary power is shown by the horizontally sectioned area. It amounts to approximately 3000

horse-power, which thus is required to maintain continuously the full power output equal to the present wheel capacity.

The diagram in Fig. 429 indicates what will be the limit of economical development, it being near the point where the regulated-flow curve takes the sharp downward bend. As the installation capacity increases

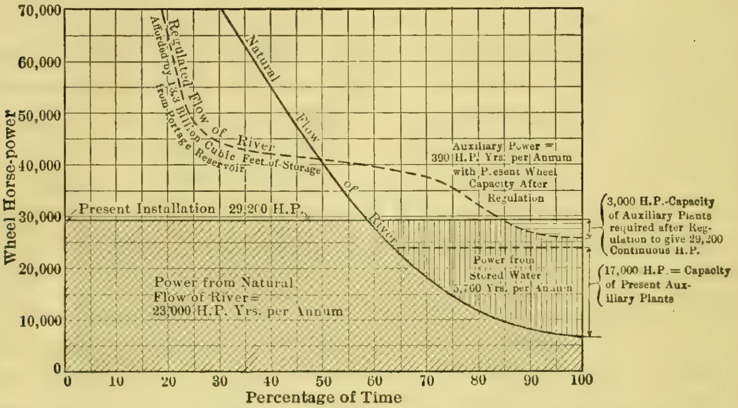

FIG. 428.—Power-percentage of Time Curves of the Genesee River at Rochester, N. Y.

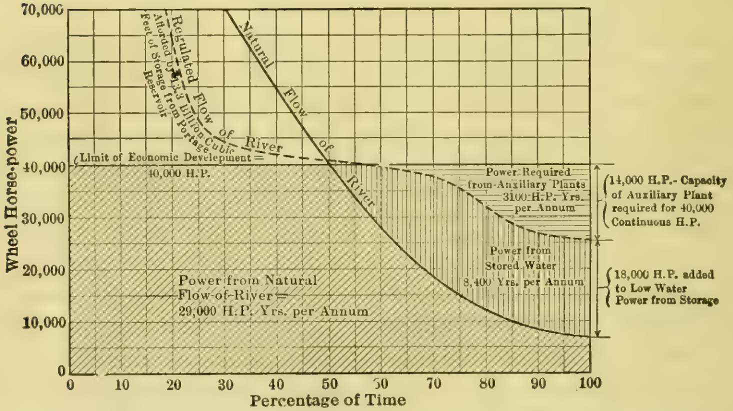

FIG. 429.—Power-percentage of Time Curves of the Genesee River at Rochester, N. Y.

above that amount, the percentage of time during which further capacity can be used, diminishes rapidly. The economical limit of capacity for the particular development in question, for a steady twenty-four-hour power after regulation, is thus seen to be approximately 40,000 horse-power, based on a 228-foot head. Such a development would run

twenty-four hours per day, 58 per cent of the time, or seven months per year on the average. The energy furnished by the natural flow each year would be 29,000 horse-power-years, from stored water 8400 horse-power-years, and from the auxiliary source 3100 horse-power-years.

The diagrams also bring out the fact that full economic advantages of the stream cannot be secured, even after regulation, without auxiliary power. They also show that a small auxiliary plant will render more additional energy available from the stream-flow after regulation than

FIG. 430.—Effect of Stored Water on Minimum Flow.

the same amount of auxiliary capacity would render available before regulation; i.e., after regulation auxiliary power is more essential to the best economic results than before regulation.

All the above has been based on a steady twenty-four-hour use of power; i.e., a load factor of 100 per cent. The general conclusions are not, however, affected by a smaller load factor; and, where there is pondage, a low load factor simply permits a larger economical installation. Thus, in the above case, with a load factor of 62 per cent the economical development would be about 64,000 horse-power.

A point in connection with water-storage problems which is not always realized is that, while a given quantity of water in storage will raise the minimum flow of the stream a certain definite amount, a further addition of that same quantity of storage, when put into the stream, will not raise the minimum flow by anything like the first quantity, because its use will have to be distributed throughout a longer period of time in the year. Therefore, as storage reservoirs continue to be built out, the increment in the minimum flow becomes less and less, which means that as the development of storage reservoirs progresses, the economical outlay per unit of storage becomes less and less,

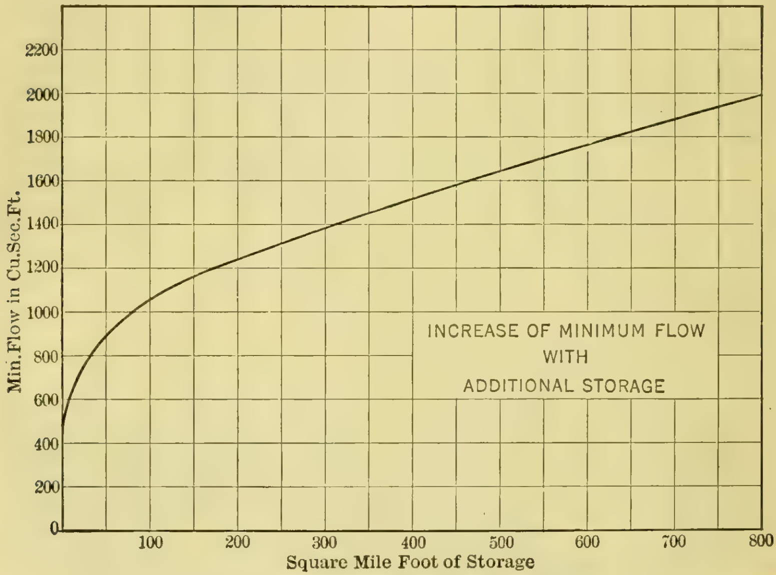

Fig. 431.—Increase of Minimum Flow with Additional Storage.

and the time comes when it becomes cheaper to increase the minimum flow by means of an auxiliary steam plant.

This may be illustrated by the diagram, Fig. 430, which represents a typical hydrograph or river-flow curve. It will be noted that the minimum flow shown by this curve is 470 cu. sec. ft. The introduction of 100 square mile feet of stored water will raise the minimum flow to 1100 cubic second-feet, a difference of 630 cubic second-feet. If additional stored water in units of 100 square mile-feet is now introduced, the figure clearly shows the decreasing amount by which the minimum flow is increased. It is, however, to be distinctly understood that this figure applies solely to the minimum rate of stream-flow and

does not mean a proportionately lower volume of water available for power production.

This decrease in minimum flow increment is shown by the curve Fig. 431, which carries the stored water up to 800 square mile-feet, resulting, in this particular instance, in the minimum flow of 2000 cubic second-feet, as against 470 cubic second-feet without storage.

AUXILIARY STATIONS

In the previous section it was shown that the full economic advantage of the stream, even with storage regulation, cannot be secured without a source of auxiliary power. Such auxiliary stations may be divided into four classes according to their utilization, although, in reality, they may not differ essentially, as some stations may serve two or three different purposes simultaneously.

Class I. *Stand-by Stations*, which are intended to take care of the load in case of a breakdown to the hydro-electric machinery or the transmission lines.

Class II. *Low-water Stations*, which are intended to supplement the load during low-water periods.

Class III. *Peak-load Stations*, which are intended to carry peak loads.

Class IV. *Base-load Stations*, which are intended to operate continuously, the water power being supplemental to the steam power.

Prime Movers. There are four kinds of prime movers which may be used for auxiliary stations; the steam turbine, the steam engine, the gas engine and the oil engine. Of these, the steam-turbine is used almost exclusively; but the question of deciding on the most economical and practical equipment is, naturally, a problem which involves a study of each individual case.

The auxiliary power can either be secured by operating old steam plants of the power customers, which have been shut down by purchase of power from a water-power company, or by constructing new steam-turbine plants as part of the water-power system.

Stand-by Stations. Emergency reserve stations are, as a rule, more necessary in the early days of a hydro-electric development than after the operating conditions become settled. They are essential, however, in order to provide against possible interruptions to the service, and contract provisions are often such as to make their installation almost imperative.

The size of such stations is naturally governed by the load which must be maintained under all conditions. Their location should be

close to important distributing centers, to insure their usefulness in case of breakdown of the transmission lines. For large and extended systems it may be advisable to provide two or more distributed stations, rather than one of the combined capacity.

A quick start is an essential requirement of an emergency stand-by station. It is, however, not customary to have all the boilers under fire to take over the load immediately in case of an interruption. Some of the boilers are, as a rule, kept under banked fires part of the time to secure the most important load, and the turbines are operated as synchronous condensers to improve the power-factor of the entire transmission system, which may carry a large inductive load.

Under these circumstances it is particularly easy to respond to sudden load demands, because the unit is already up to speed and in synchronism, the turbine is kept warmed up, and only a change in the field excitation is necessary to place the unit on the line, which takes only a few minutes at the most. When storms are approaching, the entire reserve equipment should be made ready to respond immediately to any emergency that may arise.

The first cost of the station should be low, while efficiency is not such an important item. Consideration should, however, be given to the possibility that the station may later be used under other operating conditions, requiring the highest efficiency. It is, therefore, often advisable to make provision in the design, from the beginning, for the possible installation, at a future date, of economizers and other labor-saving devices. With large steam-turbine units it is possible, however, to obtain the most efficient unit at practically the same cost as one of poorer efficiency. Less boiler capacity is, of course, needed with a higher turbine efficiency, and consequently a plant of high efficiency can, as a rule, be built at practically the same cost as one of lower efficiency.

Low-water Stations. The function of the auxiliary plant, when used as supplemental capacity during low-water periods, is similar to that of the storage reservoir. It converts at least a part of the secondary power, which would be available only part of the year, into primary power available at all times, thus increasing its sale value. It is also of value in making up shortage of water power from loss of head during high back-water caused by floods. Even though the peak load is somewhat in excess of the power corresponding to the minimum stream-flow, enough pondage can usually be provided to take care of daily fluctuations. This, of course, is only possible when the average or integrated load over the twenty-four-hour period is within the energy available from the minimum stream-flow.

The problem, therefore, really resolves itself into two questions: First, in the case of a plant already in operation, to what extent shall an auxiliary supply be provided to convert the variable power supply into a continuous supply? Second, in case of a new development, for what capacity shall it be built?

Both cases involve a study of the stream-flow and the load conditions, the first cost and annual operating charges for the hydro-electric plant of different capacities, as well as the corresponding charges for auxiliary plants of the required capacities. In the first case, the cost of the auxiliary supply for various degrees of insurance is determined and compared with the increased earnings obtained by converting the secondary power into primary. In the second case, the problem may be considered from several different points of view. For example, one may start out with the assumption that the total cost per kilowatt and year shall be a minimum; or, if all the power produced can be sold in the market at a certain price, one may undertake to determine the plant capacity at which the profit becomes a maximum. In the case of a new development, the cost per kilowatt decreases as the capacity increases, and an increase in the annual cost per kilowatt of the auxiliary plant is accompanied by a decrease in the annual cost of the hydraulic plant. A point may, therefore, be reached at which the sum of the two is a minimum, and this would fix the most economical capacity of the development and, hence, the point of greatest profit for a given market price of energy. The entire problem of determining the economical capacity of a combined hydro-electric and steam-power plant is very complicated. An excellent treatise on this subject, offering a new method of solution, was presented by Dr. C. T. Hutchinson before A.I.E.E., February, 1914, and the reader is referred to the same for further information.[1]

The size of the auxiliary station is determined by the difference between the demand curve and the stream-flow curve, except where storage is available, in which case the stream-flow as affected by the same should be used.

In order to obtain the best results, the method of operation also deserves a careful consideration. In this connection, R. C. Muir in the *General Electric Review* for June, 1913, makes the following recommendations: " In order to get the best economy out of the steam station it must operate at practically a constant load corresponding to full load on one or more units. In order to get the best economy out of the water-power station with the water available during low-water periods, the

[1] See also an article by H. S. Putnam, A.I.E.E., June, 1917.

highest water level attainable—in other words the maximum head—must be maintained at all times.

" It is impossible to conform to both of these requirements, especially where the minimum stream-flow capacity and the steam-station capacity combined are not sufficient to carry the peak load. In this case the steam plant can be operated at practically a constant load, using the water power during the peaks and storing water during the balance of the time. With high-head plants the head gained by storage is not of importance; so that the steam plant can be operated most economically on constant load, allowing the water power to take the peaks. With low-head plants having considerable storage capacity, both plants can be operated advantageously during the low-water period. Here again the water power should carry the peaks, and the steam-plant should be operated at constant load over a sufficient part of the day so that the water level will not be materially affected. This method of operation will prove much more economical, both as regards fuel used and labor required, than the method of carrying heavy loads on the steam plant during the peaks, thereby requiring more boilers and machines in service and, consequently, more fuel and operators.

" The term ' peaks ' is intended to cover heavy load periods of the daily load curve, and not the momentary load fluctuations. Assuming equal governor or speed regulation and equal flywheel effects, these momentary load fluctuations are divided between the stations in proportion to the total capacities of the generators operating in each station. The flywheel effect of the steam turbine is usually the larger and the steam turbine governor is the more sensitive. The steam turbine station will, therefore, ordinarily take more of the momentary fluctuation than its proportionate capacity in operation.

" Some fuel can be saved in developments of this kind by carefully observing the rainfall within the drainage area of the stream developed. In case of rainfall within this area, the steam plant can be shut down immediately and all the load taken over by the hydraulic plant at the expense of reducing the level of the reservoir. The increased stream-flow will again fill the reservoir. Rainfall at the head waters of a large stream would not materially increase the stream-flow at the development for some time; and, consequently, a considerable saving in fuel would thus be effected. During the dry season, water flowing over the dam means fuel wasted; and, therefore, if enough reliance could be placed in weather forecasts to anticipate rainfalls, the steam plant could be shut down in time, so that the reservoir level would be reduced sufficiently to take care of the increased flow without wasting any more over the dam than necessary."

Peak-load Stations. The function of the auxiliary plant used to carry the daily peaks of load on the system is similar to that of pondage above the water-power plant, increasing the operating load factor and, consequently, the output from water. In the case of the supplemental plant, the first cost and relative economy of generation must be governed by the proportion of the total output of the system to be carried by the auxiliary plant, i.e., the higher the percentage carried by the auxiliary plant, the more important becomes the economy of generation and the less important the first cost and resulting fixed charges.

Base-load Stations. Where the conditions are such that the average power demand exceeds the capacity of the hydraulic plant it is usually preferable to operate the auxiliary steam plant continuously, the water power then being supplemental to the steam power. Low operating costs are essential for this type of plant and, as far as the operation is concerned, the recommendations given for the low-water plants also apply in this case.

INTERCONNECTION OF SYSTEMS

The interconnection of hydro-electric transmission systems is also a step in the right direction, as demonstrated in our southern states, where not less than seven large systems are tied together, furnishing power to each other on an " interchange " contract basis. The advantages of this are obvious. The peak loads of the different systems may not coincide, the minimum stream-flow may occur at different times on the different watersheds, common steam reserve stations may be used, and, in general, the operation may be so improved that a most efficient and reliable service can be rendered to the customers of all the systems so tied together.

In some cases groups of established systems, although located in vastly different localities, may be brought together under one holding company; and to the creation of such companies may, in many instances, be attributed the high-class service and financial success of our small and medium-sized light and power systems. The economies due to a central management, the benefits of the best technical and expert advice, applied even to the smallest central station, the cumulative effect of active, up-to-date new-business campaigns at every point, all have contributed to an improved and cheaper service to the consumer; and without the facilities of such a control they could exist only in the larger communities. Another very important advantage is the great problem of financing all these undertakings and providing funds for extensions to meet the ever-growing demand of the public for electric service. It

is possibly in providing ready financial facilities for these purposes that the holding company performs its most important function.

In order to give the people the best service and the lowest rates, all public utilities must, of necessity, be natural monopolies, and the public-service regulation is a recognition by the State of the essentially monopolistic character of these enterprises. The favorable showing of virtual monopolies in reducing the cost of electric power is due mainly to a reduction in the capital expenses, lower operating costs, and in no less degree to the reduced risk to the investor. By effective safeguards and a well-considered policy of public control, electric securities have become one of the most desirable investments, and there is every indication that efficient public-service regulation will make possible even further reductions in the cost of electric-power production of public-service utilities.

INVESTIGATION OF AN ENTERPRISE

The following points cover broadly the important items upon which an investor must have information in order to judge intelligently of an offering to finance an enterprise. For a more complete treatise of the subject the reader is referred to Francis Cooper's book, "Financing an Enterprise."

I. *Nature of Enterprise.*

1. Is the basis of the enterprise sound?
2. Is the business or undertaking profitable elsewhere?
3. What competition or opposition will be met?
4. What peculiar advantages does it enjoy over these others?
5. Can it be conducted profitably under existing conditions?

II. *Plan of Organization.*

1. In what state organized?
2. What is the capitalization?
3. Is the capitalization reasonable?
4. Has the stock been issued in whole or in part and, if so, for what?
5. Is the stock offered for sale full-paid and non-assessable?
6. Has any of the stock preferences?
7. Is any of the stock unissued or held in the treasury?
8. Who has stock control?
9. Are the rights of smaller stockholders protected?
10. Are there any unusual features in charter or by-laws?

III. *Present Condition of Enterprise.*

As to Property:

1. What properties or rights are controlled?
2. What is their value and how estimated?
3. Are these properties or rights owned, or held under lease, license, grant, option or otherwise?
4. If owned, are titles perfect?
5. Are there any incumbrances on the properties or rights?
6. If not owned, are the holding papers in due form?
7. If not owned, are the terms of holding reasonable, satisfactory and safe?
8. In event of liquidation, what would be worth of property?

As to Operation:

1. What operations have been or are now carried?
2. What have been the results?
3. What difficulties, if any, have been encountered?
4. What is demand for the product or operation of the enterprise?
5. What is present status of the enterprise?
6. Are proper books kept?

As to Finance:

1. What are the present assets and their actual value?
2. What debts, claims, fees, rents, royalties or other payments or obligations are now due or are to be met and carried?
3. From what resources are these to be met?
4. Who handles the moneys and under what safeguards?
5. What are or will be the running expenses, salaries, etc.?

IV. *Management.*

Directors:

1. How many members in the board?
2. Who are these members?
3. What is their past record and present business status?
4. Who are the active members of the board?
5. Who, if any, are inactive?
6. Are meetings regularly held and attended?

7. Who compose the Executive Committee, if any, and what are its powers?
8. Are the directors stockholders and, if so, to a material amount?

Officers:

1. Who are the officers?
2. What are their previous records?
3. What are their special present qualifications?
4. Are they able to work together without friction?
5. What compensation do they receive or are they to receive?
6. Are they interested in the enterprise beyond their salaries?

V. *Plan of Operation.*

1. What is the general plan of operation?
2. What special reasons, if any, led to its adoption?

VI. *Disposition of Money Asked for.*

1. Does the money from sale of stock go into the treasury of the company?
2. If any does not go into the treasury, to whom does it go, and for what purpose?
3. Of money going into the treasury, what proportion goes into active development and operation?
4. What part goes to pay off existing debts, obligations and claims?
5. What part, if any, goes to pay for promotion expenses, commissions, etc.?
6. How is the development and operating money to be applied?
7. Is the amount asked for sufficient to accomplish the desired results?
8. Will it place the company on a self-supporting or profitable basis?

VII. *The Proposition.*

1. Is the general proposition a fair one?
2. Is the price of stock or bonds reasonable?
3. How do these prices compare with any former prices?
4. If common stock is offered, do preferred stock, bonds or other profit-sharing obligations take precedence and to what amount?

5. What reserve of profits will be retained before dividends are to be declared?
6. If preferred stock is offered, is it cumulative; does it vote; when is it redeemable, and at what price? What sinking fund provision is made for redemption and are any peculiar provisions attached? Do any bonds or other obligations take precedence of the preferred stock?
7. If bonds are offered, what interest is paid, and when and where; upon what property are they secured and when and how are they paid; is the trustee or trust company of repute; under what conditions are the bonds foreclosable; when, and how are they or may they be redeemed; are there any other securities taking precedence, and are there any peculiar provisions in deed of trust?

VIII. *General.*

1. What is the previous history of the enterprise or the property or undertaking on which it is based?
2. If inventions enter prominently, what is the previous record of the inventor?
3. By whom are the statements made and is the party making them reliable?
4. Are there any contracts or obligations not now effective by which the enterprise will subsequently be affected?

COST OF HYDRO-ELECTRIC POWER PLANTS

The cost of water power depends upon a great variety of factors, the essential feature of the design of the plant being to keep the cost within reasonable limits, so that the fixed charges, which constitute by far the greatest part of the power cost, shall not be excessive. The allowable cost of a water power can obviously not be more than the cost of producing the same amount of power by some other means, usually steam. The cost of generating the power should, furthermore, not be confused with the cost of power delivered. In addition to the cost of producing the power in the generating station, there are the expenses involved in distributing the same to the customers, often amounting to several times the cost of production, especially with hydraulic developments, where the power must be transmitted for great distances at high voltages to the market center, there stepped down to a moderate

distributing voltage, and again stepped down at the point of utilization to the voltage required for the power or lighting load. It is the cost of these transformations, transmission and distribution, besides the general expense, which makes the cost of power to the customer so much higher than the cost of actually producing the power at the generating station busbars.

The cost of the plant varies through the widest possible limits, depending on its location as regards facilities for construction and for transmission, the quantity of water and regularity of flow, the total head, conditions of the labor market, both as to quality and supply, etc. The dam and headworks are the principal items of the cost.

There are usually more elements of chance and more unknown factors in a hydraulic development than in a steam plant, and these facts should be taken into consideration and properly cared for in making up the cost estimate. In many instances cost figures must be obtained from similar work under similar conditions, and the dependence to be placed on the source of information must be duly considered and weighed. Each case must be carefully examined and studied from the conditions bearing directly upon it, and the deductions made accordingly. For a very complete classification of the construction and operating accounts, the reader is referred to the report by the N.E.L.A. Accounting Committee for 1914.

The total cost of a hydro-electric plant may be properly divided into three parts, viz.:

1. Development expenses.
2. Physical costs.
3. Overhead charges.

Development Expenses. These include all of the preliminary expenses incidental to the building up of the project and not directly involved in the actual construction of the property. They include expenditures on account of promotion, incorporation and organization, condemnation and other legal expenses, as well as cost of surveys, expert estimates, etc.

The cost of securing money is also an important item in the development of a property. By this is not meant the interest and dividends which are paid on the securities of the company to the stockholder and bondholder, and which are essential to make future issues marketable, but the actual costs to the utility of placing its securities in the hands of the public. This cost of securing the money should be distinguished from promoters' services and from bond discount. The latter is an adjustment between the amount paid by the public for the bond and

its face value, due to the difference of the interest rate of the bond and the interest rate prevailing at the time of the sale of the bond, and it may occur a number of times during the life of the corporation. The cost of securing money is a very different thing, and only comes once—when the original capital is acquired. That such costs are legitimate and must be recognized cannot fairly be denied. The existence of numerous banking and brokerage houses specializing in public-utility securities shows that money must be spent to secure money, just as it is spent to purchase generators, cable, land or any of the tangible construction elements of a property.

The losses incurred in the sale of securities, that is, brokerage and discounts, should, of course, also be included.

The development expenses will sometimes amount to as high as 20 per cent of the cost of the physical plant, depending, of course, on the attractiveness of the undertaking and the rate at which the securities can be disposed of.

Physical Costs. These should cover the actual costs of constructing the plant, including material, apparatus and labor. The cost of each unit of the plant elements in its final position is composed not only of its first cost but of all other items of expense which are necessarily involved. These may be any or all of the following: Freight, storehouse cost, inspection, assembling or fitting, transportation from storehouse to work and distribution, labor of placing element in position, transportation of men and tools to work, lost time of men during travel or wet-weather, losses on tools and material. After the cost has been estimated as closely as possible, it has become an accepted rule to add a general percentage of the same to cover contingencies, omissions and errors. This percentage is frequently estimated as 10 per cent and sometimes higher, depending on the uncertainties involved in the proposition.

The physical equipment includes:

Land and water rights.

Hydraulic construction:

Dam, intake, forebay, water conductors, etc.

Generating station:

Building, hydraulic and electric equipments, etc.

Transmission lines.

Substations.

Distributing system.

Auxiliary steam station.

Overhead Charges. Besides the above expenses for the development and actual construction of the physical plant, there are others

which must be considered as a part of the total cost of any complete development. These are termed overhead charges and are as follows:

Engineering and superintendence.
Organization.
Legal expenses.
Taxes and insurance.
Interest during construction.
Working capital.

Engineering and superintendence should cover all costs of architecture and engineering. This includes all designs and drafting, plans and supervision of construction, as well as all other items which properly come under this department. They vary from 3 to 5 per cent of the construction cost.

Organization expenses should cover the cost of organization and administration for construction, including general office expenses. They generally amount to from 3 to 5 per cent.

Legal expenses incurred during the construction period should be distinguished from those included under development expenses. They should cover only such legal work as may be necessary in obtaining the rights needed to carry out the construction.

Taxes must be paid on the property from the time of purchase, usually months or even years before the development is completed. Likewise, insurance must be paid and should include not only fire insurance, but casualty insurance, covering both employees and public liability. The estimate of these expenses can be accurately made from prevailing rates. Taxes amount to about one-half of 1 per cent and insurance about the same amount.

Interest accruing, during construction, on the idle capital represented either by cash or plant, must be included in the estimate. The length of time for which to compute the same will naturally vary with the time required for the construction, but as a rule it is figured at the full annual rate for one-half the construction period.

A reasonable amount of working capital must, of course, be provided for carrying on the business and must be considered as a part of the property.

From the above it is seen that the overhead charges form a large percentage of the cost of developing a system and may approximately be taken as from 20 to 30 per cent of the physical cost.

Cost data on hydro-electric plants are scarce, and when they are obtained the greatest caution must be exercised in using them for estimating other projects. This is especially true at present, in view of

the wide price fluctuations which have taken place during the past few years. It is obvious, moreover, that the present market conditions must be considered far from steady. The costs are greatly affected by local conditions, as for example, the nature of the soil in determining the cost of excavation, the price paid for labor, freight and transportation charges, market value of raw and other material, apparatus, etc.

Figure 432 gives approximate unit costs of hydro-electric generating

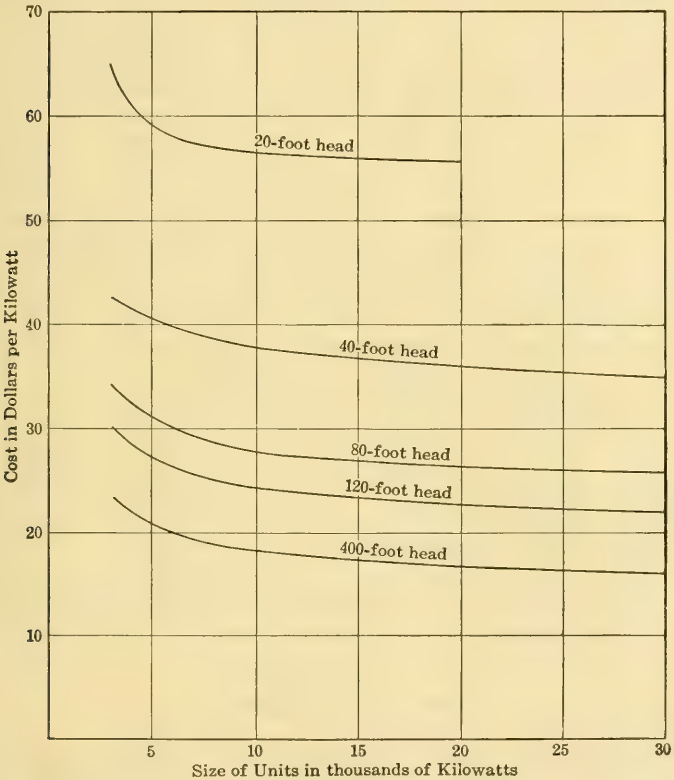

FIG. 432.—Estimated Unit Cost for Complete Hydro-Electric Equipment.

equipments, completely installed, for different operating heads and for generating units ranging in size from 5000 to 30,000 kw. These costs cover turbines, generators, low-tension switching equipment and wiring, interest during construction, superintendence, engineering and contingencies, but not power-house building with substructure foundations, dam or headworks. They are applicable to all units except the first, for which a development charge of 8 per cent should be added. These costs are based on information contained in the Super Power

Report, but as those figures were made up in accordance with prices prevailing in 1919, the values have been reduced 20 per cent, so as to approximately represent present-day (1923) conditions.

The costs given in the following are the same as contained in the First Edition of this book, and are based on conditions prior to 1916. Since that time costs have increased greatly, and because of the fluctuating nature of commodity prices it is considered inadvisable to include any new cost data. Should the plants given be duplicated at the present writing, the increased cost would be anywhere from 50 to 100 per cent. These costs were based both on actual costs and on estimates under normal pre-war conditions, and the reader must exercise great caution and discrimination in their use.

Estimated Cost of 600 Kw. Hydro-electric Power Station

It is proposed to install two units, each comprising a 500-H.P. turbine operating under a 60-foot head and driving a 300-kw. generator. There are to be two separately driven exciter units and complete switching equipment, but no step-up transformers. The dam is already provided and is not included in the estimate.

Penstock and flume, including headworks, connections, tunnel, etc	$22,500
Regulating tank, inluding housing	1,500
Power station; foundation and buildings complete with interior work and fittings	9,800
Staff house and miscellaneous	3,000
Equipment in power-house, consisting of two 500-H.P. turbines with governors, generators, exciters, switching, equipment, etc	30,200
Total	$67,000
Add for contingencies, engineering, supervision and inspection, 12 per cent, say	$ 8,000
Grand total	$75,000

Annual Cost of Operation

Overhead charges:		
Yearly installment of principal and interest. Debenture to be retired in thirty years at 5 per cent	$4,875	
Maintenance account, being an amount set aside yearly against major repairs, renewals and reasonable extensions, $2\frac{1}{2}$ per cent	1,875	
		$6,750
Operating charges:		
Salary, superintendent and general office expenses	$2,000	
Wages of operators at power station	2,200	
Supplies and minor repairs	900	
		$5,100
Total annual cost		$11,850
Or approximately $20 per kw.-year		

Municipal Hydro-electric Plant of City of Sturgis, Mich.

Capacity, 1100 Kw.

This development consists of a hollow reinforced concrete spillway dam, 308 feet long and 24 feet high. This spillway connects with an earth enbankment 400 feet long and 24 feet high. The power-house contains two 550-kw. 2300-volt generators driven by two 844-H.P. turbines, and a 40 kw. exciter driven by a 67-H.P. turbine. The head is 22 feet. Six 200-kw. oil-cooled transformers for stepping up the voltage to 22,000 are provided, also complete switching equipment and lightning arresters. The ultimate development will include two additional generating units and one additional exciter.

Cost Data Based on Ultimate Development

Items.	Total Cost.	Cost per H.P. at Wheel Shaft.	Cost per Kw. at Switch-board.
Power-house and machinery	$110,000	$32.56	$45.90
Spillway	22,000	6.50	9.16
Tailrace	20,000	5.93	8.36
Embankment	8,000	2.36	3.33
Bridge changes	8,000	2.36	3.33
Transmission line	20,000	5.93	8.37
Real estate	50,000	14.81	20.90
Substation and incidentals	12,000	3.55	5.01
Totals	$250,000	$74.00	$104.36

Actual Cost of a 4800-H.P. Development Operating under 90 Feet Head

This plant was designed to utilize the water flowing from a large storage reservoir primarily built for domestic and industrial service. It comprises four 48-inch cast-iron penstocks discharging into four 1200-H.P. horizontal turbines, each direct-connected to a 1000-kv.a. (800-kw. 0.8 P.F.), 60-cycle, 13,200-volt generator operating at a speed of 400 R.P.M. The exciter equipment consists of two 60-kw. turbine-driven units.

The first cost of the installation was $227,474, itemized as follows:

Station building	$113,786
Foundations of turbines and generators	7,883
Total station cost	$121,769
Turbines and generators	$70,574
Labor and materials	5,043
Penstocks and valves	1,375
Venturi meters	6,212
Traveling crane	2,500
Total equipment	$99,704
Lightning arresters and outgoing line equipment	$6,001
Total	$227,474
Per H.P	$47.50
Per kw	71.00

Fixed Charges and Operating Expenses (Yearly)

Labor, 1 electrical engineer, 1 operator, 2 helpers, 1 helper part time	$5,531
Fuel for heating building	86
Repairs and appliances	354
Oil and waste	87
Small supplies	262
Taxes	2,675
Interest at 6 per cent	11,374
Depreciation, station and machinery, 4 per cent	4,475
Depreciation on transmission equipment, 2 per cent	120
Total	$24,964
Daily output in kilowatt-hours	18,000
Total cost per kilowatt-hour	0.46 cent

Estimated Cost of a 6000-H.P. Development Operating under a 27-Foot Head

This development is assumed to comprise two 3000-H.P. vertical-shaft turbines driving two 2500-kv.a. (2000-kw., 0.8 P.F.) 2300-volt generators operating at a speed in the neighborhood of 75 to 80 R.P.M. Two three-phase transformer units of capacities corresponding to the generators are provided, the high-tension transmission voltage being 33,000. Provision is also made in the building for future installation of a third generator unit. It is intended that this plant is to be erected in connection with an existing dam on a navigable stream, thus doing away with the necessity of any pipe line or similar structures to carry

the water to the power-house; neither do the figures include any allowance for dam or spillway.

Cost Estimate

Electrical equipment	$80,000	
Delivery and erection	7,500	
		$87,500
Hydraulic equipment	$55,000	
Delivery and erection	5,000	
		60,000
50-ton crane, oil and water piping and miscellaneous equipment in place	$8,500	8,500
Concrete foundations, hydraulic tubes, headrace, etc	55,000	
Building, exclusive of foundation	32,000	
Excavation	6,000	
		93,000
5 miles double-circuit line on steel towers	$35,000	35,000
Contingencies (10 per cent)		28,400
Interest and insurance during construction		15,000
Engineering and superintendence		20,000
Total		$347,400
Per H.P.		$58.00
Per kw		87.00

Estimated Cost of a 6000-Kw. Hydro-electic Development Operating under a 47-Foot Head

This development contemplates a hollow reinforced concrete dam, 465 feet long and about 55 feet high, including spilling and sluiceways. An intake structure with controlling devices is to be provided in connection with the dam, and the water is to be led therefrom through an open concrete-lined canal, 2600 feet long and with a cross-sectional area of 525 square feet, to a forebay. The forebay is divided in three sections provided with gates and trash racks, and there will be three penstocks, 10 feet 6 inches in diameter and 265 feet long.

The power-house equipment comprises three 3500-H.P. turbines with governors, driving three 2000-kw. generators with direct-connected exciters. Provision is also made for transformers, switching equipment and necessary station auxiliaries, such as crane, etc.

Estimated Cost of Plant

Main dam and headworks	$313,660	
Canal, including lining	62,000	
Forebay	23,000	
Penstocks	35,750	
Power-house	61,000	
Machinery:		
Turbines and governors	42,000	
Generators and exciters	52,000	
Transformers and switching apparatus	36,000	
Total		$625,410
Engineering and contingencies	$94,690	
		$720,000
Interest during construction	28,000	
Grand total		$748,100

The total capital cost of the plant, including the proportion of the cost of creation of storage, also the proportion of the cost of a duplicate transmission line, and proportion of a transformer station and equipment is:

Capital cost of plant	$748,100.00
Transmission lines and station equipment	64,700.00
Storage	103,000.00
Total capital cost	$915,800.00
Annual charges:	
1. Interest on capital invested, assuming financing is done on bonds at 6 per cent sold at par	$54,900.00
2. Sinking fund to retire bonds in thirty years reinvested at 4 per cent, say 1¾ per cent	16,050.00
3. Depreciation on plant adjusted between general works and equipment to provide for major repairs and renewals	13,700.00
4. Operation and maintenance, including management, superintendence, wages for operators of plant, transmission line, receiving station, storage regulation, minor repairs, supplies, and upkeep, etc	20,650.00
Total annual charges	$105,300.00
Cost per kw.-year, delivered	17.50

Cost of the Minidoka Power Station of United States Reclamation Service

Capacity, 7000 Kv.A.

The power-house is a reinforced concrete structure with steel roof trusses and purlins covered by matched lumber and galvanized corrugated iron. It measures 149 feet in length, 50 feet in width and 90 feet in height. It contains five 2000 H.P. main turbines operating under a head of 46 feet, driving five 1400-kv.a. 2200-volt generators at a speed of 200 R.P.M. There are also two 180-H.P. turbine-driven exciters and each main generator is directly connected to a three-phase transformer, stepping up the voltage to 33,000. Complete switching and lightning-arrester equipment is included in the estimate, but no allowance is made for the dam, this forming part of the irrigation system.

Cost of Power-house

	Total Cost.	Cost per Kw.
Building	$82,000	$11.70
Hydraulic machinery	73,000	10.40
Electrical machinery	83,000	11.80
Freight and hauling	26,200	3.75
Erection	55,500	7.90
Tailrace	60,000	8.60
Roads and telephone lines	7,300	1.10
Camp and permanent quarters	23,200	3.35
Engineering and incidentals	11,100	1.55
Administration charges, etc	15,000	2.15
Total	$436,300	$62.30

Annual Cost of Operation

Item.	Expense per Year.
Operation:	
Labor	$5,700
Supplies	950
Repairs:	
Labor	900
Supplies and material	300
Superintendence, clerical, camp, etc	1,700
General expense and administration	450
Operating expense	$10,000

A depreciation of 5 per cent ($21,800) has also been charged to this development. There is no charge for taxes or interest, the undertaking being done by the Government. Assuming 7 per cent for interest and taxes, the total operating expenses would amount to $62,000. A total of about 15,000,000 kw. hr. was delivered during one year, thus corresponding to a cost of $0.0041 per kw. hr.

Actual Cost of 20,000-Kv.A. Hydro-electric Power Development of the City of Tacoma, Washington

This development consists of a concrete dam approximately 45 feet high and a spillway of 260 feet, intake, racks, regulating gates, and a settling channel, the last-named being 780 feet long, 40 feet wide and 20 feet deep. From the settling basin the water is carried through an 8×8-foot tunnel, 10,000 feet long, to a regulating reservoir approximately 500×500 feet, having a capacity of about 3,000,000 cubic feet available for use during peak loads. Each main turbine has a separate riveted-steel penstock about 780 feet long and ranging in size from 78 inches at the top to 48 inches at the gate valves in front of the turbines. The two exciter wheels are supplied from one 24-inch pipe which divides in the generator room.

The power-house consists of three buildings of the common wall type of construction of concrete and brick, with galvanized-iron roof supported by steel roof trusses. There are four 8000-H.P. horizontal main turbines operating under a 415-foot effective head at 450 R.P.M., driving four 5000 kv.a. three-phase, 60-cycle, 6600-volt generators. There are also two 300-H.P., 400-R.P.M. turbines, two 200-kw.-125-volt exciters, and twelve 1667-kw.-$\frac{6600}{55000}$-volt water-cooled step-up transformers arranged in four banks, also the necessary switching and lighting arrester equipment.

The entire cost of the development was as follows:

Generating Plant

Water rights	$30,000.00
Hydro-power plant, land	168,696.50
Building, fixtures and grounds	208,621.33
Dam, intake, flumes, reservoirs, penstocks	1,156,728.24
Equipment	200,640.66
Total	$1,764,686.73

Substation

Equipment	$85,577.20
Building, fixtures and land	110,619.40
Total	$196,196.60

Transmission

Land	$66,226.65
Equipment	118,193.23
Sundry	2.89
Total	$184,422.77

General Expenditures

(During Construction of Plant)

Office furniture and fixtures	$2,993.91
Engineering and superintendence	95,866.87
Injuries and damages	85.00
Interest	83,860.47
Miscellaneous	26,872.00
Total	$209,678.25
Grand total	$2,354,984.35

Cost of Hydro-electric Plants

E. V. Pannell in *Electrical News* for February 15, 1917, gives the following capital cost of four undertakings, that of the fifth being estimated. The costs are separated in five items, which, for comparison are also shown graphically in Fig. 433.

	Dam & Forebay	Penstocks	Machinery	Buildings	Eng'g. Interest Etc.	Total
A	38	6.4	15.5	6.6	22	88.50
B	26		10	6.6	11.7	54.30
C	39	6.5	25.5	30	10.5	111.50
D	15.1	13.7	30.5	14.4	5.3	79.00
E	40	15	15	15	15	100.00

Fig. 433.—Diagram Showing Cost in Dollars per Kw. of Hydro-electric Plants.

Plant A	60,000 kw.	600 ft. head
Plant B	18,000 kw.	90 ft. head
Plant C	30,000 kw.	164 ft. head
Plant D	2,500 kw.	60 ft. head
Plant E (est.)	30,000 kw.	100 ft. head

The different items cover:

1. Dam and forebay, including connecting flumes or tunnels and all preliminary de-watering, excavation, concrete, masonry and sluicing.

2. Penstocks and values.

Cost of City of Seattle Municipal Hydro-electric Plant

(Journal Electricity, Power and Gas, July 18, 1914)

General Costs

Division of Plant.	Cost.	Cost per Kw. on Basis of 15,500 Kw. Capacity.
Wood crib dam	$61,863.80	$3.99
Penstocks	299,471.59	19.32
Power station	354,387.44	22.86
Transmission lines	232,629.62	15.01
City substations	242,096.21	15.62
Lake union auxiliary station	95,550.32	6.16
Total generating system	$1,285,998.98	$82.96

Detail Costs

Division of Plant.	Capacity, Kw.	Cost.	Unit Cost, per Kw.
Wood crib dam	9,000	$ 61,863.80	$ 6.87
Penstocks, combined	11,000	299,471.59	27.23
No. 1 Penstock, complete	3,600	84,475.79	23.40
15,407 ft. 49 in. wood stave pipe, complete in place	......	33,044.16	
1,061 ft. 48 in. steel pipe, 308,000 lbs., complete	......	14,386.01	
16,468 lineal ft. grading and filling	......	37,045.62	
No. 2 penstock, complete	7,400	214,995.80	29.00
15,865 ft. 68 in. wood stave pipe, complete	......	131,561.78	
1902 ft. 48 in. steel pipe, with Y-connection, valves and cross-over to smaller pipe	......	19,587.27	
Two 36-in. standpipes, 65 and 70 ft. high	......	2,316.31	
16,816 lineal ft. grading and filling	......	61,530.44	
Cedar Falls generating station, total	13,500	354,387.44	26.30
Power-house buildings, station, switch house, transformer house and freight shed	......	47,829.77	
Employees' cottages	......	10,386.82	
Two 8000-H.P. turbines with hydraulic valves, governors and relief valves, complete in place	10,000	53,296.55	5.33
Two 2400-H.P. Pelton wheels, with valves and governors, complete	3,500	28,200.00	8.05
Two 5000-Kw. generators, complete in place	10,000	39,422.00	3.94
Two 1750-Kw. generators, complete in place	3,500	23,782.00	6.50
Two 75-Kw. exciters, with Pelton wheels and governor	150	5,383.00	35.80
One 150-Kw. exciter with Girard wheel	150	4,500.00	30.00
Switchboard, complete	13,500	11,042.45	.82
2300-volt wiring, busses and switches	13,500	30,348.29	2.25
Nine 1500-Kw., 60,000-volt transformers, in place	13,500	74,649.17	5.54

COST OF CITY OF SEATTLE MUNICIPAL HYDRO-ELECTRIC PLANT—*Continued*

Division of Plant.	Capacity, Kw.	Cost.	Unit Cost, per Kw.
60,000-volt wiring and switches	40,000	25,547.79	.64
Transmission lines, total	40,000	232,629.62	5.82
No. 1 transmission line, total	13,000	119,012.72	9.18
Right of way for both lines	......	40,490.39	
1515 poles and arms, in place	......	21,584.04	
4605 insulators	......	19,938.29	
117,500 lbs. No. 2 copper wire	......	28,480.24	
Two telephone lines; one of No. 10 copper, one of No. 14 iron, on power line poles, complete	......	8,519.76	
No. 2 transmission line	27,000	112,889.99	4.18
732 poles, with arms, in place	......	21,943.69	
2256 insulators, in place	......	7,699.37	
374,700 lb. No. 4–0 stranded copper wire	......	78,044.53	
Telephone line $\frac{3}{16}$ in. plow steel cable, on power line poles	......	4,475.49	
Linemen's cottages, incomplete	......	726.91	
City substations, total	12,000	242,096.21	20.17
Main substation, Seventh avenue and Yesler Way, total	12,000	216,063.89	18.00
Substation building	......	30,081.26	
60,000-volt switches and wiring	40,000	7,250.00	.18
Eight 1500-Kw. 50,000-volt transformers in place	12,000	56,350.00	4.69
15,000-volt and 2500-volt wiring and switches	12,000	46,155.83	3.85
Station switchboard	12,000	17,500.00	1.46
Twelve 2500-volt feeder regulators on commercial circuits	600	14,750.00	24.58
500-Kw. direct-current motor generator set	500	15,500.00	31.00
Twelve 100-lamp constant-current transformers with switches and wiring	720	15,250.00	21.20
500-ampere hour, 500-volt storage battery	500	11,576.80	23.15
60-Kw. motor generator	60	1,650.00	27.50
Four outlying substations	3,300	26,032.32	7.90
Seven 15,000 to 2500-volt transformers, total 3300 Kw	3,300	15,582.26	4.73
Five constant-current transformers, complete	300	4,925.00	16.42
Three 2500-volt feeder regulators	150	3,330.00	22.20
Station wiring and switches	3,300	545.06	.16
Four buildings, corrugated iron	......	1,650.00	
Lake Union Auxiliary Station	1,900	95,550.32	50.30
Building complete	1,900	10,044.45	5.27
2500-H.P. Pelton-Francis water wheel with governor and valves, complete	1,900	8,914.82	4.80
1500-Kw., 2500-volt alternator with exciter, complete	1,900	10,675.85	5.62
Station, wiring, switches and switchboard	1,900	8,150.25	4.30
3400 ft. 40-in. steel penstock, complete, 400,000 lbs	1,900	41,456.51	21.80
Special tie-line, 2500-volt, two-phase, 819,000 c.m. aluminum, complete	......	16,308.44	

3. Generating machinery, including turbines with governors and regulating gates, generators including exciters, transformers, switch gear.
4. Building for power-house, switch-house, tailrace, etc.
5. Engineering, interest, contingencies.

Estimates of Cost of Hydro-electric Developments

Pages 738 to 745 contain, in considerable detail, the cost of construction and operation of several water-power projects as contained in Bulletin 5, prepared by the State Engineer's office of Oregon.

The unit prices used in the estimates of cost were determined as follows:

Concrete. Proportions for massive concrete: One part Portland cement, two and one-half parts sand, five parts broken stone of size corresponding to gravel, and two and one-half parts broken stone corresponding to cobblestone size. For canal lining and other thin concrete the larger size will not be used.

Material.	Price, F.O.B. Portland.	Local Freight, Railway and Wagon and Storage.	Total.
Cement, per barrel	$1.60	$0.60	$2.20
Lumber, per thousand	25.00	6.00	31.00
Sand, per cubic yard	....	....	1.50
Broken stone, per cubic yard (Crushed on the job)	....	....	1.50

Estimate of Cost per Cubic Yard of Concrete

For What Used.	Cement.	Sand.	Stone.	Forms.	Labor.	Total.
Canal lining	$3.00	$0.70	$1.40	$1.90	$3.00	$10.00
Forebay, etc	3.00	.70	1.40	1.90	3.00	10.00

Dams

The estimated cost of concrete varied with volume as follows:

More than 200,000 cubic yards	$ 6.00
100,000 to 200,000 cubic yards	6.50
50,000 to 100,000 cubic yards	7.00
25,000 to 50,000 cubic yards	8.00
10,000 to 25,000 cubic yards	9.00
Under 10,000 cubic yards	10.00

Rock Excavation

Dam foundations, not including estimate for cofferdam, per cubic yard	$1.25
Canals and forebays, per cubic yard	1.25
Tunnels, etc., per cubic yard	8.00 to 15.00

Steel Work

Trash racks (Bessemer-steel rails):	
Factory price, per pound	$0.01½
Freight, per pound	.01½
Fabrication and placing	.02
Total	$0.05
Pipe work for penstocks:	
Factory price, plate, per pound	$0.01¾
Freight	.01½
Fabrication and placing, per pound	0.03¼ to 0.03¾
Total	$0.06½ to 0.07

Hydraulic Equipment. Horizontal turbine water wheels in pairs. Estimate based on figures obtained from two independent manufacturers. Prices include freight charges and cost of installation. Relief valves are estimated separately.

Electrical Equipment. Prices on electrical equipment are based upon estimates of manufacturers of electrical machinery, and are as follows:

Generators, all of the 3-phase, 2300-volt, 60-cycle, type per kw. output:	
For heads of under 40 feet	$8.00
For heads of under 40 to 80 feet	7.00
For heads of 80 to 120 feet	6.00
For heads of 120 feet	5.00
Exciter turbines and exciters, per kw. output, whole plant	.80
Switchboard and accessories, cables, etc., per kw. output, whole plant	2.25
Transformers, oil insulated and water cooled, 2,300–60,000 volts, per kw. output, whole plant	4.00

Cost of Georgia Railway and Power Company's Development at Tallulah Falls, Ga.

(A.I.E.E., October 11, 1915)

The development consists essentially of an artificial reservoir of a capacity of 1,400,000,000 cubic feet formed by two reinforced concrete buttress dams located near Mathis, Ga., seven miles from the diverting dam and intake at Tallulah Falls; an artificial reservoir at Tallulah Falls having an available pondage of 63,000,000 cubic feet formed by a cyclopean masonry dam of the gravity type located some 60 feet below the tunnel intake; a tunnel with a cross-sectional area of 151 square feet, 6666 feet long leading from the intake at the Tallulah reservoir to the surge or pressure tank at the top of the gorge immediately above the

(*Continued on page 746*)

Oak Springs Power Site

Estimate of Cost:		
Power head		32 ft.
Flow used for estimate		3,700 c. f. s.
Brake horsepower (80 per cent eff.)		10,824 (8100 Kw.)
Dam:		
Total height, 50 feet; length of crest, 480 feet; length of spillway, 200 feet.		
Masonry, 15,310 cubic yards, at $9.00	$137,790.00	
Excavation, 6443 cubic yards, at $1.25	8,054.00	
Cofferdam	70,000.00	
Incidentals and special foundation contingencies	34,156.00	
		$250,000.00
Forebay, etc.:		
Excavation, 12,000 cubic yards, at $1.25	15,000.00	
Concrete walls, 1500 cubic yards at $10.00	15,000.00	
Trash racks, 12,000 pounds steel, at 5c	600.00	
Stop logs	400.00	
		31,000.00
Headgates, Penstocks, etc.:		
10 sliding headgates, set in place, at $750.00	7,500.00	
10 hydraulic relief valves, in place, at $1,200.00	12,000.00	
800 feet $\frac{5}{16}$-inch steel penstock, 12 feet diameter, 530 pounds, per foot at 5½c., $34.45	27,560.00	
		47,060.00
Power-house and draft tubes:		
Power-house, reinforced concrete, 8100 Kw., at $5.00 per Kw	40,500.00	40,500.00
Summation		$368,560.00
Engineering and contingencies, 25 per cent		92,140.00
Interest during construction, 5 per cent approx		25,300.00
		$486,000.00
Hydro-electrical machinery:		
10 horizontal water-wheel units, 1085 H.P., in place, speed 200 R.P.M., at $10,000.00	100,000.00	
10 750-Kw. generators, 200 R.P.M. at $8.00	60,000.00	
Exciter turbines and exciters, in place, at 80c. per Kw	6,480.00	
Transformers, at $4.00 Kw	32,400.00	
Switchboard and accessories, cables, etc., at $2.25 per Kw	18,225.00	
Traveling crane, 30-ton	9,000.00	
Quarters, water supply, etc	20,000.00	
Summation	246,105.00	
Engineerng and contingencies, 25 per cent	61,525.00	
Interest during construction, approx	6,370.00	
		314,000.00
Summation		800,000.00
Railway, realignment, 8 miles, at $50,000.00		400,000.00
Total construction cost		$1,200,000.00
Total amount of power, E.H.P., 10,824.		
Construction cost, per E.H.P	110.87	
Assumed right of way cost, per E.H.P	5.00	
Cost of development, per E.H.P		$115.87

LOCKIT POWER SITE

Estimate of cost:

Power head	70 feet	
Flow used for estimate	4,500 c. f. s.	
Brake horse-power (80 per cent eff.)	28,630 (21,500 Kw.)	

Dam:		
Total height, 94 feet; length of crest, 720 feet; length of spillway, 225 feet.		
Masonry, 56,014 cubic yards, at $7.00	$392,098.00	
Excavation, 15,533 cubic yards, at $1.25	19,417.00	
Cofferdam	50,000.00	
Trash racks, 30,000 pounds steel, at 5c	1,500.00	
Incidentals and special foundation contingencies	56,985.00	
		$520,000.00
Headgates, penstocks, etc.:		
10 sliding headgates, set in place, at $750.00	7,500.00	
10 hydraulic relief valves, in place, at $1,200.00	12,000.00	
1,650 feet $\frac{5}{16}$-inch steel penstock, 11 feet diameter.. 500 pounds per foot at 6½c., $32.50	53,625.00	
1450 feet $\frac{7}{16}$-inch steel penstock, 10 feet diameter, 450 pounds, per foot at 7c., $31.50	45,675.00	
		118,800.00
Power-house and draft tubes;		
Power-house, reinforced concrete, 21,500 Kw., at $5.00 per Kw	107,500.00	107,500.00
Summation		$746,300.00
Engineering and contingencies, 25 per cent		186,575.00
Interest during construction, ½ of 3 years, at 4 per cent, 6 per cent approx		57,125.00
		$990,000.00
Hydro-electrical Machinery:		
10 horizontal water wheel units, 2860 H.P., in place, speed 360 R.P.M., at $15,000	150,000.00	
10 2500-Kw. generators, 350 R.P.M., at $7.00 per Kw	175,000.00	
Exciter turbines and exciters, in place, at 80c. per Kw	17,200.00	
Transformers, 21,500 Kw., at $4.00 per Kw	86,000.00	
Switchboard and accessories, cables, etc., at $2.23 per Kw	48,000.00	
Traveling crane, 30-ton	9,000.00	
Quarters, water supply, etc	20,000.00	
Summation	505,200.00	
Engineering and contingencies, 20 per cent	101,000.00	
Interest during construction, 3 per cent approx	18,800.00	
		625,000.00
Total construction cost		$1,615,000.00
Total amount of power, E.H.P., 28,630.		
Construction cost, per E.H.P	56.41	
Assumed right of way cost, per E.H.P	10.00	
Cost of development, per E.H.P		$66.41

MECCA POWER SITE

Estimate of cost:

Power head	90 feet
Flow used for estimate	3,400 c. f. s.
Brake horse-power (80 per cent eff.)	27,760 (20,750 Kw.)

Dam:		
Total height, 110 feet; length of crest, 650 feet; length of spillway, 160 feet.		
Masonry, 64.787 cubic yards, at $7.00	$453,509.00	
Excavation, 10,920 cubic yards, at $1.25	13,650.00	
Cofferdam	40,000.00	
Incidentals and special foundation contingencies	22,841.00	
		$530,000.00
Forebay, etc.:		
Trash racks, 12,000 pounds steel, at 5c	600.00	
Stop logs	400.00	
		1,000.00
Headgates, penstocks, etc.:		
8 sliding headgates, set in place, at $900.00	7,200.00	
8 hydraulic relief valves, in place, at $1,200.00	9,600.00	
1400 feet $\frac{5}{16}$-inch steel penstock, 12 feet diameter, 530 pounds per foot at 6½c., $34.45	48,230.00	
600 feet $\frac{7}{16}$-inch steel penstock, 11 feet diameter, 615 pounds, per foot at 7c., $43.05	25,830.00	
		90,860.00
Power-house and draft tubes:		
Power-house, reinforced concrete, 20,750 Kw., at $5.00 per Kw	103,750.00	103,750.00
Summation		$725,610.00
Engineering and contingencies, 25 per cent		181,402.00
Interest during construction, 6 per cent approx		62,988.00
		$970,000.00
Hydro-electrical machinery:		
8 horizontal water wheel units, in place, 3470 H.P., speed 400 R.P.M., at $10,400.00	83,200.00	
8 2500-Kw. generators, 400 R.P.M., at $6.00 per Kw.	120,000.00	
Exciter turbines and exciters, in place, at 80 c. per Kw	16,600.00	
Transformers, at $4.00 per Kw	83,000.00	
Switchboard and accessories, cables, etc., at $2.25 per Kw	46,687.00	
Traveling crane, 40-ton	15,000.00	
Quarters, water supply, etc	20,000.00	
Summation	$384,487.00	
Engineering and contingencies, 20 per cent	76,895.00	
Interest during construction, 2 per cent approx	8,618.00	
		470,000.00
Summation		$1,440,000.00
Railway realigned, 6 miles at $50,000		300,000.00
Total construction cost		$1,740,00.000
Total amount of power, E.H.P., 27,760.		
Construction cost, per E.H.P.	62.68	
Assumed right of way cost, per E.H.P.	5.00	
Cost of development, per E.H.P		$67.68

White Horse Rapids Power Site

Estimate of Cost:

Power head	138 feet	
Flow used for estimate	3,700 c. f. s.	
Brake horse-power (80 per cent eff.)	47,200 (35,100 Kw.)	
Dam:		
Total height, 122 feet; total length of crest, 440 feet; length of spillway, 160 feet.		
Masonry, 56,762 cubic yards, at $7.00	$397,334.00	
Excavation, 13,771 cubic yards, at $1.25	17,214.00	
Cofferdam	40,000.00	
Incidentals and special foundation contingencies.	55,452.00	
		$510,000.00
Forebay, etc.:		
Excavation, 10,000 cubic yards, at $1.25	12,500.00	
Concrete walls, 2500 cubic yards, at $10.00	25,000.00	
Trash racks, 120,000 pounds steel, at 5c	600.00	
Stop logs	400.00	
		38,500.00
Diversion line:		
Canal excavation, 260,000 cubic yards, at $1.25	325,000.00	
Canal lining, 4400 cubic yards, at $10.00	44,000.00	
		369,000.00
Headgates, penstocks, etc.:		
10 sliding headgates, set in place, at $900.00	9,000.00	
10 hydraulic relief valves, in place, at $1,200.00	12,000.00	
1100 feet $\frac{5}{16}$-inch steel penstock, 11 feet diameter, 500 pounds per foot at 6½c., $32.50	35,750.00	
600 feet $\frac{3}{8}$-inch steel penstock, 10 feet diameter, 495 pounds per foot at 7c., per foot $34.65	20,790.00	
		77,540.00
Power-house and draft tubes:		
Power-house, reinforced concrete, 35,100 Kw., at $5.00 per Kw. (made the same as Frieda)	176,000.00	176,000.00
Summation		$1,171,040.00
Engineering and contingencies, 25 per cent		292,760.00
Interest during construction, ½ of 2 years, 4 per cent approx		60,200.00
		$1,524,000.00
Hydro-electrical machinery:		
10 horizontal water wheel units, in place, 4720 H.P., speed 450, at $22,000	220,000.00	
10 3500 Kw. generators, 450 R.P. M., at $5.00	175,000.00	
Exciter turbines and exciters, in place, at 80c. per Kw	28,080.00	
Transformers, at $4.00 per Kw	140,400.00	
Switchboard and accessories, cables, etc., at $2.25 per Kw	78,975.00	
Traveling crane, 40-ton	15,000.00	
Quarters, water supply, etc	20,000.00	
Summation	$677,455.00	
Engineering and contingencies, 20 per cent	135,491.00	
Interest during construction, 20 per cent approx	16,054.00	
		829,000.00
Railway realigned, 9 miles, at $50,000.00		450,000.00
Total construction cost		$2,803,000.00
Total amount of power, E.H.P., 47,200.		
Construction cost, per E.H.P	59.38	
Assumed right of way cost, per E.H.P	5.00	
Cost of development per E.H.P		$64.38

Metolius Power Site

Estimate of cost:		
Power head	210 feet	
Flow used for estimate	3,400 c. f. s.	
Brake horse-power (80 per cent eff.)	64,960 (48,700 Kw.)	
Dam:		
Total height, 236 feet; length of crest, 420 feet; length of spillway, 125 feet.		
Masonry, 183,000 cubic yards, at $6.50	$1,189,500.00	
Excavation, 37,570 cubic yards, at $1.25	46,962.00	
Cofferdam	75,000.00	
Wagon roads	25,000.00	
Incidentals and special foundation contingencies	164,;38.00	$1,500,500.00
Forebay, etc.:		
Excavation, 8000 cubic yards, at $1.25	10,000.00	
Concrete walls, 1500 cubic yards, at $10.00	15,000.00	
Trash racks, 20,000 pounds steel, at 5c.	1,000.00	26,000.00
Diversion line:		
Tunnel excavation and lining, 300 feet by 15 feet by 20 feet, at $150.00		45,000.00
Headgates, penstocks, etc.:		
10 sliding headgates, set in place, at $900.00	9,000.00	
10 hydraulic relief valves in place, at $1,200.00	12,000.00	
500 feet $\frac{5}{16}$-inch steel penstock, 12 feet diameter, 530 pounds per foot, at $6\frac{1}{2}$c., $34.45	17,225.00	
500 feet $\frac{9}{16}$-inch steel penstock, 10 feet diameter, 565 pounds per foot at 7c., $39.55	19,775.00	58,000.00
Power-house and draft tubes:		
Power-house, reinforced concrete, 48,700 Kw., at $5.00 per Kw	243,500.00	243,500.00
Summation		$1,873,000.00
Engineering and contingencies, 25 per cent		468,250.00
Interest during construction, 8 per cent		208,750.00
		$2,550,000.00
Hydro-electrical machinery:		
10 horizontal water wheel units, in place, 6496 H.P., speed 400 R.P.M., at $24,000.00	240,000.00	
10 5000-Kw. generators, 400 R.P.M., at $5.00 per Kw	250,000.00	
Exciter turbines and exciters, in place, at 82c. per Kw	40,000.00	
Transformers, at $4.00 per Kw	194,800.00	
Switchboard and accessories, cables, etc., at $2.25 per Kw	109,575.00	
Traveling crane, 40-ton	15,000.00	
Quarters, water supply, etc.	20,000.00	
Summation	$869,375.00	
Engineering and contingencies, 20 per cent	173,875.00	
Interest during construction, 30 per cent approx.	36,750.00	1,080,000.00
Total construction cost		$3,630,000.00
Total amount of power, E.H.P., 64,960.		
Construction cost, per E.H.P	55.88	
Assumed right of way cost, per E.H.P	5.00	
Cost of development, per E.H.P		$60.88

JEFFERSON CREEK POWER SITE

Estimate of cost:		
Power head	400 feet	
Flow used for estimate	1,000 c. f. s.	
Brake horse-power (80 per cent eff.)	36,363 (27,100 Kw.)	
Dam:		
Total height, 20 feet; length of crest. 90 feet; length of spillway, 80 feet.		
Masonry, 1000 cubic yards, at $10.00	$10,000.00	
Excavation, 300 cubic yards, at $2.00	600.00	
Cofferdam	800.00	
Incidentals and foundation contingencies	8,600.00	
		$20,000.00
Forebay, etc.:		
Excavation, concrete walls, trash racks, etc.		25,000.00
Diversion line:		
Canal excavation and lining, 8 feet by 30 feet by 41,000 feet, at $30.00		1,230,000.00
Headgates, penstocks, etc.:		
4 sliding headgates, set in place, at $900.00	3,600.00	
4 hydraulic relief valves, in place, at $1,200.00	4,800.00	
1000 feet $\frac{5}{16}$-inch steel penstock, 10 feet diameter, 450 pounds, per foot at 6½c., $29.25	29,250.00	
1000 feet $\frac{3}{8}$-inch steel penstock, 9 feet diameter, 440 pounds, per foot at 6½c., $28.60	28,600.00	
1000 feet, $\frac{9}{16}$-inch steel penstock, 8 feet diameter, 500 pounds per foot at 7c., $35.00	35,000.00	
		101,250.00
Power-house and draft tubes:		
Power-house, reinforced concrete, 27,100 H.P., at $5.00 per Kw		135,500.00
Summation		$1,511,750.00
Engineering and contingencies, 25 per cent		377,938.00
Interest during construction, ½ of 2 years, at 4 per cent approx		80,312.00
		$1,970,000.00
Hydro-electrical machinery:		
4 horizontal water-wheel units, in place, 9091 H.P., speed 360 R.P.M., at $31,000.00	124,000.00	
4 7000-Kw. generators, 365 R.P.M., at $5.00 per Kw.	140,000.00	
Exciter turbines and exciters, in place, at 80c. per Kw	21,680.00	
Transformers, at $4.00 per Kw	108,400.00	
Switchboard and accessories, cables, etc., at $2.25 per Kw	60,975.00	
Traveling crane, 40-ton	15,000.00	
Quarters, water supply, etc.	20,000.00	
Summation	$490,055.00	
Engineering and contingencies, 20 per cent	98,011.00	
Interest during construction, 2 per cent apprcx	11,934.00	
		600,000.00
Total construction cost		$2,570,000.00
Total amount of power, E.H.P., 36,363.		
Construction cost, per E.H.P.	70.67	
Assumed right of way cost, per E.H.P	5.00	
Cost of development, per E.H.P.		$75.67

power-house; five steel penstocks 5 feet in diameter, each of which serves a 17,000-H.P. Francis type water turbine in the power-house. Five three-phase, 60-cycle 6600-volt, vertical generators are direct-connected to these water wheels.

The electrical energy from these machines is stepped up from 6600 volts to 110,000 volts for transmission by five banks of three 3333 kw. single-phase static transformers of the water-cooled type and is transmitted over two outgoing lines.

Reservoir. The reservoir covers 834 acres, most of which was heavily timbered prior to the construction period. It was cleared of timber, brush and other debris before the impounding began, at a cost of $21 per acre, represented by $8.35 for cutting and $12.65 for gathering and burning.

Reservoir Dams. There are two reinforced buttressed dams, the largest 660 feet in length, 93 feet high to the crest of the spillway and 114 feet to the top walkway. The other dam is much smaller. The quantities involved in the construction of these two dams were 2,200,000 pounds of steel reinforcing, and 38,000 cubic yards of concrete.

The following figures give the cost per cubic yard of these two dams:

Quarry	$ 1.611
Crushing and mixing	.818
Freight and engine service	1.110
Placing concrete	.744
Reinforcement	1.447
Placing reinforcement	.823
Labor	3.746
Cement	2.777
Sand	.126
Plant, erecting and maintenance	1.496
Small tools and supplies	1.123
Lumber	1.034
Miscellaneous expenditures	1.617
Superintendence and overhead	1.443
Total	$19.915

Diverting Dam. This dam is of the gravity type, built of cyclopean masonry, heavy stone forming a little over one-third of the mass. The dam is 110 feet high from the stream stratum and has a length of 426 feet. The spillway section is 280 feet in length, made up of ten 28-foot openings between concrete piers. There was used in this dam 39,000 cubic yards of concrete which was placed by the contractors at $4.80 per cubic yard, the actual cost possibly being about $3.70 per cubic yard. The cost of bridge piers and flashboards is additional. The contract price for the excavation work was $1.50 per cubic yard.

Intake. The intake is a self-contained reinforced structure divided by partitions into five sections. The construction involved about 7000 cubic yards of excavation, mostly rock, and 2670 cubic yards of concrete. The detailed cost of excavation and concrete for the intake was as follows:

	Per Cubic Yard.
Excavation:	
Lumber	$0.974
Explosives	0.065
Miscellaneous supplies	0.123
Transportation	0.071
Liability insurance	0.049
Removing debris	0.235
Total	$1.517
Concrete:	
Labor	$3.902
Cement	1.982
Lumber	0.794
Freight	0.042
Transportation	0.203
Liability insurance	0.136
Erection of plant	0.400
Crusher	1.280
Miscellaneous supplies	0.205
Removing debris	0.086
Total	$9.030

Tunnel. The tunnel is 6666 feet long, and has a net area of 151 square feet inside the concrete lining. About 75 per cent of the tunnel was driven by the top-heading method, and the remainder by the lower heading or stopping method, which proved to be much cheaper. The total excavations amounted to 56,000 cubic yards.

The unit cost of excavating 39,831 yards of this tunnel was as follows:

	Per Cubic Yard.
Labor	$3.833
Explosives	0.604
Lubricants	0.019
Freight	0.087
Piping	0.026
Drill repairs	0.172
Miscellaneous supplies	0.237
Transportation	0.247
Liability insurance	0.181
Miscellaneous charges	0.066
Depreciation on equipment	0.150
Power	0.306
Total	$5.928

The concrete lining of the tunnel called for the placing of 18,966 cubic yards of concrete, the unit cost of the lining being:

Labor	$ 5.061
Cement	1.970
Miscellaneous materials	0.405
Lumber	0.136
Freight	0.065
Transportation	0.155
Liability insurance	0.165
Royalty on mixers	0.413
Miscellaneous cost	0.245
Crushing stone	1.991
Quarrying stone	0.858
Plasterers	0.202
Cleaning tunnel	0.376
Total	$12.042

The entire tunnel was grouted with grout consisting of one part cement to one and one-half parts sand. The cost of the grouting was $1.436 per cubic yard of concrete lining, made up of the following unit figures:

Item.	Cost per Linear Foot of Tunnel.
Labor	$2.209
Cement	1.649
Transportation	0.001
Liability insurance	0.065
Miscellaneous supplies	0.155
	$4.079

The following figures give the approximate total cost of the tunnel per linear foot:

Excavation	$44.44
Concrete lining	34.20
Grouting	4.08
Adits and shafts	1.91
Compressor plants, spur tracks and operation	8.99
Steel forms	2.94
Total	$96.56

Forebay. The forebay is a reinforced concrete structure, 30×70 feet and 95 feet deep. The excavation involved some 4750 cubic yards of rock, and the thickness of the concrete in the walls of the tank varied from 3 to 6 feet. Some 700 tons of steel reinforcement were used.

The cost of the rock excavation at the forebay was as follows:

	Per Cubic Yard.
Labor	$1.620
Explosives	0.106
Transportation	0.089
Liability insurance	0.067
Miscellaneous supplies	0.246
Miscellaneous expenses	0.038
	$2.166

The concrete lining of the forebay shows the following unit figures:

	Per Cubic Yard.
Labor	$1.680
Cement	1.920
Lumber	0.117
Freight	0.012
Transportation	0.013
Liability insurance	0.049
Miscellaneous expenses	0.178
Crushing stone	1.569
Miscellaneous supplies	0.033
	$5.571

Power-plant Building. The power-plant buildings are constructed with a concrete substructure and a structural steel framework enclosed with full brick walls as a superstructure. The generator building is 186 feet long, 42 feet 3 inches wide and 49 feet high above generator floor. The switch-house is 277 feet long, 46 feet wide and 103 feet high.

There are five vertical reaction turbines operating under an effective head of 580 feet at a speed of 514 R.P.M., driving five 12,000-k.va. 6600-volt generators with direct-connected exciters. There are also five transformer banks each consisting of three 3333-kv.a. single-phase transformers for stepping up the voltage to 110,000.

The unit cost of the power-house buildings and installed equipment is given in the following, the cost of the hydraulic and electrical equipment being based on the installed capacity of 50,000 kw. on the original rating and that of the buildings and other equipment on 60,000 kw., the ultimate capacity of the original rating.

	Per Kw. Capacity.
Buildings and foundations:	
Rock excavation	$ 0.428
Concreting foundations and substructure	2.114
Structural steel	0.522
Handling and unloading	0.030
Erecting	0.109
Brick, sand and cement	0.460
Handling, mixing and laying	0.960
Windows and doors	0.176
Handling and erecting	0.003
Tile roofing	0.115
Concrete tile floors	0.400
Miscellaneous material	0.186
Miscellaneous labor and transportation of men	0.234
Painting	0.124
Plumbing	0.053
Building inspection	0.142
Tailrace:	
Rock excavation	0.197
Cribbing	0.017
Concreting tailrace walls	0.242
Total	$6.512
Equipment:	
Hydraulic equipment	$ 6.582
Handling and erecting	0.463
Electrical equipment and erection	6.236
Auxiliary equipment	0.999
Handling and erecting auxiliary equipment	0.105
High- and low-tension switch and bus structure	0.445
Water and oil piping system	0.244
Total equipment	$15.074

Grouping the above items under a more condensed form, we have:

Tailrace	$ 0.456
Buildings—substructure	2.542
Buildings—superstructures	3.372
Buildings—inspection	0.142
Total equipment	15.074
Cost per kw. capacity	$21.586

In addition to this cost there is a certain proportion of the temporary compressor plant, spur tracks, general tool and utility equipment, etc.,

amounting to \$1.178, which should be charged to this power-plant construction, making the total cost of the power-plant buildings and equipment \$22.76 per kilowatt capacity.

As the foregoing costs do not, in some instances, give the cost of completed structure under the various headings, the following table will supply the construction cost per kilowatt capacity of the entire power production plant, including reservoirs, dams, all hydraulic conduits, power plant and equipment, and including temporary construction plant, such as compressor plants, water system, spur tracks, etc.

	Per Kw.
Mathis dams and reservoirs	\$17.104
Intake dam and bridge	4.660
Intake	1.102
Tunnel	12.379
Forebay	2.395
Penstock tunnels and portal	0.694
Penstocks and foundations	5.568
Power plant and equipment	22.764
Total construction cost power production plant per kilowatt	\$66.666

The following gives the percentage relation of various expenses on the development as a whole, which might be applicable to any other development, and therefore does not include the cost of land or property expense:

	Per Cent.
General construction expenditure	75.575
General engineering expense	3.078
General legal expense	1.891
Interest, bonds and advances during construction	11.315
General overhead expense	1.773
General contract expense	6.368
Total	100.000

Estimate of 72,000-Kw. Generating Station at Great Falls, Potomac River, for Supplying Light and Power for the Use of United States and the District of Columbia

(From H. R. Document No. 1400)

This proposed project provides for a dam across the Potomac River at Great Falls, creating a lake or reservoir of some 3000 acres area and an operating head of 111 feet. The dam is in two parts, a spillway dam and an intake dam. The former is of the arched type, somewhat similar to the spillway section of the Gatun dam, at Panama, and comprises eighteen openings separated by piers and provided with Stoney gates. A gatehouse is arranged for on top of the intake dam, from which nine penstocks convey the water to the turbines. These are of riveted steel from $\frac{3}{8}$ to $\frac{3}{4}$-inch thickness, the inside diameter being 13 feet and the length 140 feet.

When completed, the equipment will comprise nine 12,500-H.P. single-runner vertical turbines operating at 150 R.P.M. under a head of 111 feet. These will drive nine 10,000-kv.a. (8000 kw. .8 P.F.) 3-phase, 60-cycle, 13,209-volt generators, with direct-connected exciters. Provision is further made for complete switching equipment and station auxiliaries.

The allowance in the original estimate for relocating the Chesapeake and Ohio Canal has been omitted in the following:

Estimated Cost

Spillway dam:	
Piers, superior concrete, 7540 cubic yards, at $9.00	$ 67,000
Piers, concrete, 27,800 cubic yards, at $8.00	222,000
Water-flow guides, concrete, 1850 cubic yards at $8	15,000
Dam, superior reinforced concrete, 37,400 cubic yards, at $9	337,000
Dam, cyclopean superior concrete, 36,200 cubic yards, at $5.50*	200,000
Dam, cyclopean concrete, 233,550 cubic yards, at $4.50*	1,050,000
Total masonry	$1,891,000
Excavation, rock, 115,400 cubic yards, at $2.50	289,000
Stoney gates, 18, erected, weight 1,162,000 pounds, at $0.08	130,000
Stoney gates, fittings and machinery, etc., 18 sets at $6500	117,000
Floating caisson	5,000
Foot bridge, erected, weight 833,000 pounds, at $0.08	65,000
Railing, 2850 feet, at $1.75	5,000
Total spillway dam	$2,502,000

Intake Dam and Power-house

Power-house superstructure, 2,200,000 cubic feet at 15c	$330,000
Power-house, substructure, 2,000,000 cubic feet, at 17c	340,000
Intake house, superstructure, 750,000 cubic feet, at 15c	113,000
Intake house, substructure, 471,000 cubic feet, at 17c	80,000
Cranes and railroad track	15,000
Turbines, erected, 9, at $51,000	459,000
Central lubrication system	27,000
Electrical units, 9, and switchboard etc., at $90,000	810,000
Intake dam, cyclopean concrete, 107,700 cubic yards, at $4.50 *	485,000
Excavation, intake dam, power-house, and tailrace, 475,000 cubic yards, at $2.50	1,187,500
Penstocks, 10 erected, 1,350,000 pounds, at 8c	108,000
Rack bars, 10 sets, 9350 square feet, at $1.75	16,500
Head gates, 2	5,000
3 pumps and their motors, erected	20,000
Force main, laid, 300,000 pounds, at 14c	42,000
Shore wasteway	25,000
Road and branch railroad	100,000
Total intake dam and power-house	$4,163,000

NOTE.—Prices marked thus (*) are reduced by reason of part cost being borne by rock excavation.

Summary

Spillway dam	$2,502,000
Intake dam and power-house	4,163,000
Land and water rights	1,500,000
Engineering and contingencies	585,000
Total	$8,750,000

Cost of Power

Estimate for 319.4 millions kilowatt-hours annual output, or 100,000 H.P. effective peak load.

Operation:		
Administration and labor		$60,000
Maintenance and supplies		20,000
		$80,000
Depreciation, headworks and power-house:		
1 per cent on masonry	$4,910,500	$49,105
2 per cent on steel work	438,500	8,770
3 per cent on machinery	1,316,000	39,480
	$6,665,000	$97,355
Fixed charges:		
Interest, 3 per cent, sinking fund 3 per cent, or 6 per cent on above $8,750,000		$525,000
Total		$702,355

Or 2.2 mills per kilowatt-hour of output.

Estimated Cost of 200,000 and 300,000 Horse-power Hydro-electric Developments

From Bulletin No. 5, State Engineer's Office, Oregon

Head: 200 feet minimum.

Estimate of Cost, 200,000 Electrical Horse-power Installation

River diversion:		
Temporary diversion channel:		
Excavation above elevation 885, 500,000 cubic yards, at $1.00	$500,000.00	
Excavation below elevation 885, 100,000 cubic yards, at $1.50	150,000.00	
Concrete, lining, 10,000 cubic yards, at $8.00	80,000.00	
Concrete walls, 5000 cubic yards, at $8.00	40,000.00	
Concrete, miscellaneous, 2000 cubic yards, at $10	20,000.00	
Steel reinforcing, 100 tons, at $100.00	10,000.00	
		$800,000.00
Cofferdams, earth and rock fill:		
Upper cofferdam, 300,000 cubic yards, at $1.00	300,000.00	
Lower cofferdam (first structure), 100,000 cubic yards, at $1.00	100,000.00	
Lower cofferdam (replacing structure), 100,000 cubic yards, at $1.00	100,000.00	
		500,000.00
Extraordinary contingency (insurance allowance)		500,000.00
Main dam:		
Excavation below elevation 885, 350,000 cubic yards, at $2.00	700,000.00	
Excavation above elevation 885, 50,000 cubic yards, at $1.00	50,000.00	
Concrete, 760,000 cubic yards, at $6.00	4,560,000.00	
Movable dam crest	190,000.00	
		5,500,000.00
Forebay and penstocks:		
Tunnel excavation, 32,000 cubic yards, at $5.00	160,000.00	
Tunnel lining concrete, 5000 cubic yards, at $8.00	40,000.00	
Open excavation, 200,000 cubic yards, at $1.00	200,000.00	
Forebay walls, concrete, 20,000 cubic yards, at $7.00	140,000.00	
Penstock cradles, concrete, 5000 cubic yards, at $8.00	40,000.00	
Gates, trash racks, etc	200,000.00	
Penstocks, 1500 tons, at $140.00	210,000.00	
Reinforcing steel, 100 tons, at $100.00	10,000.00	
		1,000,000.00
Power and transformer house:		
Excavation, 60,000 cubic yards, at $1.00	60,000.00	
Concrete, 20,000 cubic yards, at $8.00	160,000.00	
Concrete, 5000 cubic yards, at $12.00	60,000.00	
Reinforcing steel, 100 tons, at $100.00	10,000.00	
Roof, crane, etc	60,000.00	
		350,000.00
Right of way (assumed)		150,000.00
Summation of above items		8,800,000.00
Engineering and contingencies, 25 per cent		2,200,000.00
Interest during construction, 2½ years at 4 to 10 per cent		1,100,000.00
		$12,100,000.00
Hydro-electric equipment:		
Turbines, generators, exciters, and governors, 7 units, 25,000 Kw. each, at $200,000.00	1,400,000.00	
Switchboard, plant wiring, etc	200,000.00	
Transformers, 150,000 Kw	500,000.00	
Freight, erection and installation	400,000.00	
Summation of above items	$2,500,000.00	
Engineering and contingencies, 20 per cent	500,000.00	
Interest, ¾ yr. at 4 per cent say 3⅓ per cent	100,000.00	
		3,100,000.00
Total for project		$15,200,000.00

200,000 E.H.P. continuous development at $76.00 per E.H.P.

Estimate of Cost, 100,000 Electrical Horse-power Additional Power

Forebay, penstocks, power-house and tailrace:		
Additional, including 25 per cent for engineering and contingencies and 10 per cent interest during construction	$1,000,000.00	
Additional equipment, including 20 per cent for engineering and contingencies, and 3 per cent for interest, 100,000 H.P.	1,500,000.00	
Summation		$2,500,000.00
This is the total additional cost to supply 100,000 horse-power additional power during the part of the time for which the flow of the river is in excess of 15,000 second-feet.		
Estimated cost of storage to maintain a minimum flow of 15,000 second-feet, 500,000 acre-feet		2,000,000.00
Total additional		$4,500,000.00
Total for 200,000 H.P. project (preceding estimate)		15,200,000.00
Total for project		$19,700,000.00
300,000 E.H.P. at approximately $66.00 per E.H.P.		

Estimate of Annual Cost

For 200,000 Electrical Horse-power Continuous Development

This estimate has been made on the basis of the following assumptions: Interest rate 4 per cent, assumed life of dams, forebay, substructure of power-house, and tailrace, fifty years. Assumed life of movable crest gates, trash racks, penstocks, superstructure of power-house and equipment, fifteen years.

Annual replacement fund, for fifty-year life portion, $10,800,000 at $\frac{2}{3}$ per cent		$72,000.00
For fifteen-year life portion, $4,400,000 at 5 per cent		220,000.00
Annual interest, $15,200,000.00, at 4 per cent		608,000.00
Annual maintenance and repairs		60,000.00
Attendance and administration		80,000.00
Total annual cost, 200,000 E.H.P. development		$1,040,000.00
Annual cost per E.H.P. on basis of 100 per cent load factor	$5.20	
Additional 25 per cent	1.30	
Annual cost, if only 80 per cent of the power is used	$6.50	

These costs are based upon utilization of the power immediately upon completion of the project.

Estimate of Annual Cost

For 300,000 Electrical Horse-power Continuous Development

Based upon similar assumptions to those for the 200,000 E.H.P. development.

Annual replacement fund, for fifty-year life portion, $13,200,000 at $\frac{2}{3}$ per cent	$88,000.00
For fifteen-year life portion, $6,500,000.00, at 5 per cent	325,000.00
Annual interest, $19,700,000.00, at 4 per cent	788,000.00
Annual maintenance and repairs	90,000.00
Attendance and administration	119,000.00
Total annual cost	$1,410,000.00

Annual cost per E.H.P. of base load	$4.70
Additional 25 per cent	1.20
Annual cost if only 80 per cent of the power is used	$5.90

Estimated Cost of Proposed Columbia River Project

Capacity:

480,000 horse-power	12 months per year
600,000 horse-power	11 months per year
700,000 horse-power	10 months per year
800,000 horse-power	8 months per year

The following cost estimate on this proposed extensive development is taken from an article by Mr. L. F. Harza in the *Journal for Electricity, Power and Gas*, for March 18, 1916. Readers interested in this unusual development are referred to the long series of articles appearing in said journal during 1915 and 1916.

Contingent Margin. The total cost of each item as given in the estimates which follow all include a margin of 25 per cent to cover engineering, administration during construction, and contingencies in addition to the amounts obtained by applying the foregoing unit prices, except in the case of the generating machinery; in this case only 15 per cent was allowed, as these estimates are based upon the higher or two or more actual quotations in nearly all cases, and the manufacturer himself would furnish the engineering talent except for erection, which item has been included in the estimate.

ESTIMATE OF CAPITAL COST

Dam for closing present channel:		
Scheme A +25 per cent	$3,325,000	
Scheme B +25 per cent	2,288,000	
Scheme C +25 per cent	3,344,000	
Scheme D +25 per cent	3,056,000	
Scheme E +25 per cent	3,485,000	
Scheme F +25 per cent	3,419,000	
Use for estimate		$3,350,000
Controlling dam:		
Camere type of dam; approximate quantities as designed for 81 feet controlled depth.		
25,000 tons structural steel.		
4,000 tons cast steel.		
230,000 cubic yards of concrete.		
1 traveling gantry crane.		
Estimated cost, reduced 25 per cent, for 67 feet controlled depth plus 25 per cent contingent fund	$3,851,000	
Tainter-gate type of dam, approximate quantities as designed for 81 feet controlled depth.		
41,600 tons structural steel.		
21,800 tons cast steel.		
480 tons steel cable.		
312,450 cubic yards concrete.		
Estimated cost, reduced 25 per cent, for 67 feet controlled depth plus 25 per cent contingent fund	8,837,000	
Use for estimate of controlling dam		8,837,000
Flood channel:		
Approximate quantities:		
2,078,000 cubic yards rock excavation, above elevation 84.0 (sill of flood gates) plus 25 per cent		2,078,000
Diversion channel:		
Approximate quantities:		
1,243,000 cubic yards rock excavation for diversion channel below elevation 84.0.		
140,500 cubic yards concrete.		
810,000 F.B.M. timber for cribs.		
8,000 cubic yards rock fill in cribs.		
Estimated cost of diversion channel and closure of same plus 25 per cent		2,872,000
Ice and drift sluice, Oregon side:		
Approximate quantities:		
252,000 cubic yards rock excavation.		
28,300 cubic yards concrete.		
320 tons structural steel rollers.		
Estimated cost plus 25 per cent		452,000
Wing walls for rock fill dam:		
Approximate quantities:		
42,500 cubic yards concrete plus 25 per cent		266,000
Main floating boom and piers:		
Approximate quantities:		
11,394,000 f.b.m. of timber.		
1,055 tons of rods and drift pins.		
3,000 cubic yards concrete.		
46,000 cubic yards rock fill in piers.		
Estimated cost plus 25 per cent		493,000

Power canal:	
Approximate quantities:	
4,229,000 cubic yards rock excavation.	
136,000 cubic yards rubble walls.	
17,960 cubic yards concrete lining.	
1,000,000 cubic yards sand excavation.	
Two floating booms.	
22,000 cubic yards concrete.	
110 tons structural-steel roller dams.	
Estimated cost plus 25 per cent....................	$5,394,000
Jetty at intake to power canal:	
Approximate quantities:	
4,430,000 f.b.m. of timber.	
665,000 pounds rods and drift pins.	
2,470 cubic yards reinforced concrete.	
164,000 cubic yards rock fill.	
73,000 cubic yards sand excavation	
Estimated cost plus 25 per cent....................	285,000
Rebuilding Five Mile Lock:	
Raising walls and gates and building draw span, plus 25 per cent..................................	106,000
Forebay and power-house substructure:	
Approximate quantities	
1,584,000 cubic yards dry rock excavation.	
137,500 cubic yards rock excavation for removal of cofferdam	
429,250 cubic yards concrete.	
5,000,000 pounds steel reinforcement.	
3,500,000 pounds structural steel for penstock gates.	
2,300,000 pounds cast steel for penstock gates.	
1,024,000 pounds steel trash racks.	
24 filler gates and drain gates.	
$375,000 for cofferdamming and pumping.	
Estimated cost plus 25 per cent....................	5,852,000
Power-house superstructure:	
76 feet by 1670 feet station building.	
Fishway.	
Tunnel through building for railroad.	
Steel bridges for spanning forebay and tailrace.	
Estimated cost plus 25 per cent....................	1,475,000
Power-house machinery:	
23 vertical shaft 35,000-Kw. (50,000 Kv.A.) 25-cycle, 11,000-volt, 75-R.P.M., 3-phase generators, including stator and rotor, but not shaft or bearings.	
23 mechanically driven exciters, 500 Kw. each; switchboard, low-tension oil switches, busbars, and all miscellaneous electrical equipment.	
23 50,000-H.P. vertical shaft 75 R.P.M. turbine units, including shaft and oil bearings, governors, and oil system.	
2 250-ton traveling cranes in power house and 2 50-ton traveling gantry cranes serving penstock gates; miscellaneous small equipment.	
Estimated cost plus 15 per cent....................	12,353,000
Reconstruction of railroads:	
Total estimated cost plus 25 per cent................	687,000
Other property damage..................................	904,000
Total physical cost..................................	$45,404,000
Add for interest during one-half of five-year construction period at 4 per cent equals 10 per cent.........	4,540,000
Total estimated capital cost........................	$49,944,000
Use for total capital cost..........................	50,000,000

Annual Cost of Generating Primary Power. The following items are independent of the interest rate on capital investment:

Depreciation—Reserve fund assumed to earn 2 per cent interest and sufficient to replace all depreciable parts every fifteen years, and to refund the cost of nearly permanent structures, rock excavation, concrete, etc., every fifty years (average value 3 per cent)		$1,500,000.00
Maintenance and repairs—For maintenance and repairs on the turbine units, in addition to depreciation fund, per annum	$112,800.00	
Maintenance and repairs to generators and electrical equipment, $1\frac{1}{2}$ per cent	74,000.00	
Repairs to movable dam	50,000.00	
Painting, average of one coat per annum, 43,700 tons of exposed steel (total in use), at $1 per ton	43,700.00	
Operating suction dredge to prevent possible accumulation of sand bar at canal intake, 300 days, $100 per day	30,000.00	
Maintenance of building, replacing roof every five years plus 50 per cent for other repairs	2,400.00	
Contingent maintenance and repair expense	50,000.00	
Total for maintenance and repairs		362,900.00
Attendance and administration		100,000.00
Total annual expense exclusive of interest		$1,962,900.00

The rate of interest to be paid on the capital investment will depend largely upon the basis of financing. To show the relation of this to the annual cost of power, interest rates of 3 and 4 per cent have been assumed as representing public development under different conditions. There has also been assumed a rate of 6 per cent on securities originally discounted 10 per cent, plus 1 per cent taxes, this basis being intended to represent approximately the cost under corporate financing. The results are as follows: No sinking fund has been provided, as it is not properly chargeable to the cost of generation. The depreciation or amortization fund would provide for keeping the project permanently in first-class operating condition. A water-power property is of such unquestionable permanent value as to make it unnecessary to recover the principal in a short time as with many industrial enterprises which are subject at any time to the necessity of complete liquidation due to unforeseen competition. In the case of corporate finance, especially, a sinking fund might, however, assist in securing easier terms in marketing the securities, but in any event is amply covered by the 25 per cent contingent fund. A 50-year sinking fund drawing 2 per cent interest would involve an annual expense of $1.20 per continuous electrical horse-power.

Three per cent basis:		
Depreciation, maintenance and repairs as above........		$1,962,900.00
3 per cent interest on $50,000,000....................		1,500,000.00
Total annual charges..................................		$3,462,000.00
Annual cost per peak electrical horse-power year of base load (480,000 H.P.)................................	$ 7.22	
Add 25 per cent.......................................	1.80	
Use...	$ 9.02	
Four per cent basis:		
Depreciation, maintenance and repairs as before........		$1,962,900.00
4 per cent interest on $50,000,000....................		2,000,000.00
Total annual charges..................................		$3,962,900.00
Per peak horse-power year.............................	8.27	
Add 25 per cent.......................................	2.07	
Use...	$10.34	
Six per cent basis:		
Depreciation, etc., as before.........................		$1,962,900.00
Add for 6 per cent on securities originally sold at 10 per cent discount, equivalent to 6.67 per cent............		3,340,000.00
Add for taxes 1 per cent..............................		500,000.00
Total annual charges..................................		$5,802,900.00
Cost of power on usual basis of private enterprise per peak horse-power per year..............................	12.10	
Add 25 per cent.......................................	3.03	
Use...	$15.13	

Cost of Generation Contingent upon Sale of Surplus Power. If the sale of the surplus power is to be assumed, then an additional item of depreciation should be added to provide for the possibility of severe runner erosion for the low-head units when operating at heads above 80 feet. The value of one runner including freight and erection would be about $27,000.

About seven low-head units are required to operate at 80 foot-head to produce 800,000 H.P., with a decreasing number at the higher heads where the erosion would be most severe. If we assume to replace all seven runners every three years, the annual additional charge would be $63,000, say $75,000. This item is very small compared with the additional profit which the surplus power should bring.

It might be assumed roughly that eleven months' surplus power would be worth 80 per cent of the value of continuous power, ten months' power 60 per cent and eight months' power 30 per cent.

If the various prices now be weighted according to the amount available, and the price of primary power used as unity, there will result:

$$
\begin{array}{l}
480{,}000\times 1.00=480{,}000\\
120{,}000\times\ .80=\ 96{,}000\\
100{,}000\times\ .60=\ 60{,}000\\
100{,}000\times\ .30=\ 30{,}000\\
\overline{800{,}000}\text{ actual or }666{,}000\text{ weighted power}
\end{array}
$$

The quotient of these totals, or 0.8333, now represents the average unit value of all power, as a proportion of the value of primary power, and 666,000 represents the equivalent primary power to produce the same income. If all power were to be sold at prices bearing the above ratio to each other, the actual costs of production of primary power would then be obtained by first adding $75,000 to the annual charges and then dividing by 666,000.

Based upon 3 per cent interest:		
Former annual charge		$3,462,900.00
Add for runner depreciation		75,000.00
Total		$3,537,900.00
Add 25 per cent		884,000.00
Use		$4,421,900.00
Cost per peak primary horse-power	$6.63	
Cost per 11 months' surplus H.P	5.30	
Cost per 10 months' surplus H.P	4.00	
Cost per 8 months' surplus H.P	2.00	
Based upon 4 per cent interest:		
Former annual charge		$3,962,900.00
Add for runner depreciation		75,000.00
Total		$4,037,900.00
Add 25 per cent		1,009,500.00
Use		$5,047,400.00
Cost per primary horse-power	$7.58	
Cost per 11 months' surplus H.P	6.06	
Cost per 10 months' surplus H.P	4.55	
Cost per 8 months' surplus	2.27	
Based upon 6 per cent interest—on securities sold at 90:		
Former annual charge		$5,802,900.00
Add for runner depreciation		75,000.00
Total		$5,877,900.00
Add 25 per cent		1,469,500.00
Use		$7,347,400.00
Cost per primary horse-power		$11.02
Cost per 11 months' surplus H.P		8.82
Cost per 10 months' surplus H.P		6.62
Cost per 8 months' surplus H.P		3.31

The computations for the capital cost and cost of power for the case in which a period of ten years was allowed for building up the load, were made by starting with the initial investment necessary to deliver one-tenth of the power, and then progressively adding for each year the deficit, or difference between interest on the previously accumulated investment, operating expenses, etc., and the earnings of the year in question, to the investment of the previous year. It was necessary first to assume a price of power and after computing the transactions of the ten-year period, to then correct this assumption by a process of successive approximations until an assumption was made which provided the desired 25 per cent margin at the end of the ten-year period.

COST OF POWER [1]

The cost of hydro-electric power can be considered as made up of two parts: the fixed charges and the operating expenses. These, in turn are made up as follows:

Fixed Charges:
- Interest on investment.
- Taxes and insurance.
- Depreciation.

Operating Expenses:
- General administration.
- Labor.
- Supplies.
- Maintenance and repairs.

In estimating the cost of power, a thorough distinction must, as previously stated, be made between the cost of the same at the generating station busbars and the cost when delivered to the customer. In the former case the cost should be based on only such portions of the charges and expenses as are applicable to the generating station, while in order to obtain the cost of power delivered, the total expenses must, of course, be considered.

The rate of interest on the investment varies, and depends on the risk involved. In risky undertakings the rates of interest are higher than where greater safety obtains; if money put into new enterprises involving risk of loss were not allowed to earn any more than a normal rate of interest, it would be poor policy for the investor to put his money in such undertakings. Bonds, therefore, should draw the lowest rate of interest because, as a rule, they are safe, being secured by a mortgage

[1] See previous section for actual and estimated costs.

on the property. So, for example, many Government bonds draw only an interest of 4 per cent because there is no risk involved. The rate on public service bonds, on the other hand, is higher, averaging about 6 per cent, but, of course, when they are sold at a discount the actual interest earned by the investor is greater. The interest on the stock, however, which cannot be declared until the bond interest has been paid, should be so much higher than the normal interest that it will compensate for the lesser security. A rate at least 2 per cent higher than prevailing bank rates seems justifiable, and commissions frequently approve rates of return of 7 per cent and 8 per cent.

The second item under the fixed charges is taxes and insurance. The amount necessarily depends on the rates available, but, for estimating purposes a total of $1\frac{1}{2}$ per cent should be allowed for the complete hydraulic plant, while for steam plants 2 per cent ought to be allowed.

Depreciation is the loss in value which occurs while the property is in service, either through wear and tear or obsolescence, and a certain sum of money must be set aside annually for renewing this property. There are different methods of providing for depreciation, but the sinking fund or annuity method is best applicable to public utility properties. It provides for setting aside each year a sum that, invested at a certain rate of interest compounded annually, will equal the cost of the property, less its scrap value, at the end of its assumed life. Thus, if a certain portion of a plant costs \$10,000 and has a life of ten years, with a scrap value of 10 per cent, or \$1000, and it is desired to set aside a sum that, at 5 per cent interest compounded annually, will accumulate

TABLE LXIV

Property.	Total Life, Years.
Dams, masonry	50
Pipe lines, iron	30–40
Pipe lines, wood-stone	15–25
Power-house building, fireproof	50–75
Water-wheels	20
Generators	20
Transformers	20
Switching equipment	12–15
Miscellaneous auxiliaries	10
Transmission lines, steel towers	25–30
Transmission lines, wood poles	15
Underground cable system	20–25
Service transformers	15

an amount equal to the cost, less the scrap value, at the end of the life period, it will then be found, by referring to an annuity table, that $9000×0.0795 or $715.50 annually will produce the required amount. As the life, as well as the scrap value of the different elements varies to a considerable extent, the depreciation should be figured separately for each item, and thereafter averaged.

The useful life of the plant apparatus or equipments is purely a speculative matter; and past experience, knowledge of the art, and careful judgment must be exercised in arriving at the probable life of apparatus and property. See Table LXIV. In the Super Power Report the following values were used:

	Per Cent.
Hydro-electric power plants	3
Hydraulic works	1
Steam-electric power plants	4
Transmission lines	2
Sub-stations	4

The operating expenses, which include general administration, labor, repairs, maintenance and supplies, will vary with the amount of power manufactured, that is, the load factor. They are, however, by no means proportional to it, and form a much smaller part of the total cost than with steam stations, where the fuel expenses come in and where both labor, repair and supply items are much higher. The extensive investigations for the proposed Super Power System thus revealed the fact that, of the total production cost for the steam plants in this zone, the fixed charges were 44.5 per cent and the operating expenses, including general administration expense, 55.5 per cent. Similarly, for the hydro-electric plants it was found that 81 per cent represented the fixed charges and 19 per cent the operating and general expenses. Based on a 50 per cent load factor, the operating expenses may range anywhere from 0.3c. per kw. hr. for a small station to possibly 0.04c. or less for a very large station. It is difficult to give any definite figures, on account of the fluctuating costs of labor and supplies, but the following figures should give an approximate representation of present (1923) conditions. In view of the fact that the operating expenses, in general, only amount to about one-fifth of the total cost of hydro-electric power, a divergence from these figures will only have a small effect on the total cost.

Cost of Steam Plants and Power. The cost of steam power stations, for a very wide range in capacity, was also very carefully investigated by the Super Power Organization. These estimates were, however, based on prices prevailing in the mid-year of 1919, and in order to arrive at present day (1923) figures, a reduction of 30 per cent will probably

TABLE LXV

OPERATING EXPENSES OF HYDRO-ELECTRIC STATIONS

Station Capacity in Kw.	Operating Expenses in Cents per Kw.hr.	Station Capacity in Kw.	Operating Expenses in Cents per Kw.hr.
2,500	0.20	25,000	0.08
5,000	0.16	50,000	0.07
10,000	0.12	75,000	0.06
15,000	0.10	100,000	0.05

be approximately correct. The costs given in Fig. 434, are therefore based on the 1919 figures of the Super Power Report, reduced by 30 per cent.

The cost of steam power naturally varies greatly, depending on the

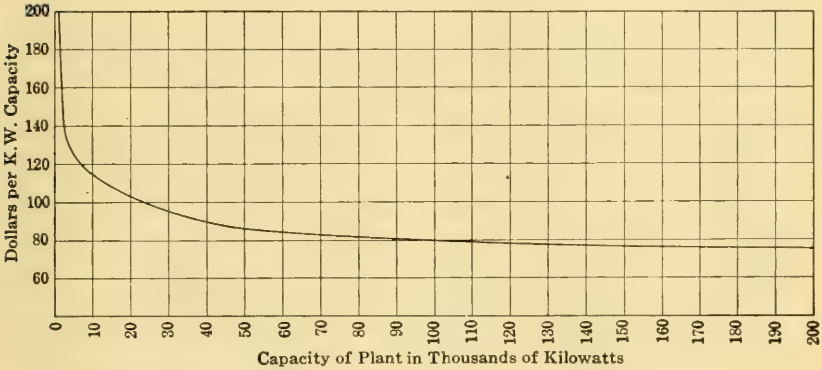

FIG. 434.—Estimated Unit Cost of Steam Power Stations.

size of plant, load factor, cost and heat value of the fuel, etc. A very complete and interesting tabulation, partly abstracted in Table LXVI, was contained in the *Electrical World* for July 15, 1922. It gives the results of a careful analysis of the operating expenses of a large number of central stations, operating under widely different conditions. Despite the many factors which influence the operating economy and production expense, it is interesting to observe how closely the results obtained follow the load factor and coal characteristics.

TABLE LXVI

Operating Economy and Production Expenses of Representative Steam Generating Stations

(Abstract from article by A. M. Perry in Electrical World, July 15, 1922)

Rating of Station, Kw.	Annual Load Factor, Per Cent.	Output, Kw.-hr., Twelve Months.	Peak Load, Kw.	B.t.u. per Pound of Fuel.	Pounds Coal per Kw.hr.	B.t.u. per Kw.hr.	Operating Expense, Cents per Kw.hr. Delivered from Switchboard.				Maintenance Expense, Cents per Kw.hr. Delivered from Switchboard.				Total * Production Expense.
							Fuel.	Wages.	Superintendence, and Misc.	Total.	Station Building.	Steam Equipment.	Electrical Equipment.	Total.	
170,000	51.0	527,121,000	118,000	......	1.62	20,250	0.532	0.069	0.026	0.627	0.011	0.045	0.002	0.058	0.685
170,000	38.4	461,809,700	137,450	13,879	1.690	23,460	0.737	0.105	0.040	0.882	0.023	0.095	0.008	0.126	1.008
150,000	43.2	493,848,800	131,000	13,218	2.020	27,000	0.896	0.114	0.0390	1.049	0.024	0.138	0.018	0.180	1.229
150,000	48.1	473,782,743	112,500	13,396	1.735	23,720	0.746	0.0670	0.024	0.837	0.007	0.052	0.019	0.078	0.915
95,000	11.2	57,026,700	58,000	12,713	2.46	31,400	0.782	0.167	0.088	1.037	0.035	0.131	0.005	0.171	1.208
60,000	44.2	239,936,000	62,000	13,124	1.75	22,950	0.363	0.062	0.028	0.453	0.004	0.027	0.003	0.034	0.487
56,000	42.3	108,829,278	29,358	10,983	2.56	28,200	0.530	0.089	0.031	0.650	0.018	0.061	0.016	0.095	0.745
53,000	51.3	127,758,800	28,400	10,350	2.39	24,800	0.700	0.055	0.023	0.778	0.007	0.077	0.006	0.090	0.868
52,000	38.2	164,464,720	49,200	12,216	1.91	23,350	0.632	0.078	0.010	0.720	0.004	....	....	0.058	0.778
50,000	45.5	201,550,584	50,650	10,147	3.28	33,300	0.361	0.072	0.059	0.492	0.014	0.116	0.097	0.227	0.719
44,500	27.6	34,017,300	28,115	14,300 11,000	2.29	31,500	0.780	0.098	0.078	0.956	0.015	0.073	0.007	0.095	1.051
36,000	28.7	78,579,120	31,200	13,960 18,500	....	33,600	0.949	0.162	0.075	1.186	0.013	0.107	0.007	0.127	1.313
29,500	38.2	59,775,632	17,970	10,043	4.47	44,900	0.648	0.116	0.029	0.793	0.005	0.061	0.022	0.088	0.881
26,150	42.1	44,405,000	12,050	9,000	4.34	39,100	0.918	0.141	0.004	1.063	0.001	0.082	0.060	0.143	1.206
22,600	47.9	45,783,090	10,900	10,330	2.53	26,200	0.920	0.120	0.080	1.120	Neg	0.260	0.070	0.330	1.450
22,500	43.0	30,134,000	16,000	14,600	1.61	23,600	0.695	0.109	0.081	0.885	0.022	0.103	0.055	0.130	1.015
20,750	34.0	17,479,655	11,700	14,353	1.94	27,800	0.800	0.192	0.044	1.036	0.012	0.057	0.011	0.080	1.116
20,500	35.7	16,903,667	10,800	14,800	2.26	33,550	1.101	0.244	0.061	1.315	0.054	0.076	0.007	0.137	1.452
20,000	59.0	47,358,299	9,200	11,350	2.89	32,800	0.707	0.155	0.089	0.951	0.012	0.079	0.038	0.129	1.080
20,000	39.7	69,623,000	20,000	13,938	1.63	22,700	0.429	0.046	0.017	0.492	0.001	0.028	0.005	0.034	0.526
18,500	41.3	20,126,100	11,100	14,500	1.94	28,200	0.855	0.130	0.023	1.008	0.006	0.034	0.007	0.047	1.055
18,000	39.0	60,269,400	17,600	13,775	2.08	28,600	0.530	0.088	0.020	0.638	0.001	0.062	0.004	0.067	0.705
16,500	36.5	36,111,820	11,300	13,500	2.67	36,100	0.876	0.162	0.022	1.060	0.022	0.119	0.023	0.164	1.224
16,100	40.7	10,701,600	6,000	14,450	2.03	29,300	1.370	0.313	0.128	1.711	0.032	0.212	0.060	0.304	2.015
13,100	35.8	5,720,680	3,650	......	2.48	......	1.100	0.340	0.105	1.545	0.021	0.090	Neg.	0.111	1.656
10,000	38.2	18,092,320	5,400	......	2.99	......	0.792	0.075	0.079	0.946	......	......	......	0.019	0.965
10,000	42.8	27,419,574	7,300	11,500	2.46	28,300	0.740	0.076	0.001	0.817	Neg.	0.003	Neg.	0.003	0.821
8,500	45.5	29,914,900	7,500	......	2.54	......	0.536	0.098	0.001	0.635	......	......	......	0.094	0.729
8,500	42.5	26,029,860	7,000	12,500	2.84	35,600	0.611	0.110	0.050	0.770	0.010	0.090	0.010	0.110	0.880
7,500	36.1	5,395,500	3,400	14,450	......	......	1.280	0.341	0.163	1.784	0.025	0.092	Neg.	0.117	1.901

* Fixed charges not included.

CHAPTER X

ORGANIZATION AND OPERATION

Management. The measure of financial success attained in a hydro-electric development is, to a great extent, determined by the skill and judgment of its management. The department heads should study the men whom they employ and also the problem of handling them to the best advantage. It should be the object of the department chiefs so to dispose both men and material that their possibilities will be best realized. An adequate system of records should be kept, showing what the several departments are doing, and promptness and completeness in this respect should be insisted upon. Regular meetings between the department heads and their men are advisable, and many companies have inaugurated suggestive systems by which suggestions for the improvement of the operating and service conditions are invited, prizes being given at regular intervals for the best suggestions received.

The organization of a hydro-electric company naturally varies considerably, not only depending on the size of the system, but also on the nature of the same. An idea of the extensive force required by a large company, such as the Great Western Power Company, is obtained by referring to the chart given in Fig. 435.

Operating Force. The selection and maintenance of an efficient and reliable operating force is also essential, as upon the same depends the quality of service rendered. Most modern systems of any size have a method of operation which corresponds to that of a train despatcher on steam railroads, and where many different plants are attached to the same network, this becomes practically necessary. A load despatcher is located at some convenient point, which often is not at a power-house, and is placed in charge of the whole system and personally directs every operation in all stations. He is in telephone communication with all operators and keeps a record of the changes and connections made in each part of the system, by means of a system of pins and markers on a large map or plan of the circuits and apparatus of the plant. He receives, at regular intervals, readings of loads, water conditions, etc., which he marks down on the record sheet before him, and from these records and recording instruments in his office he

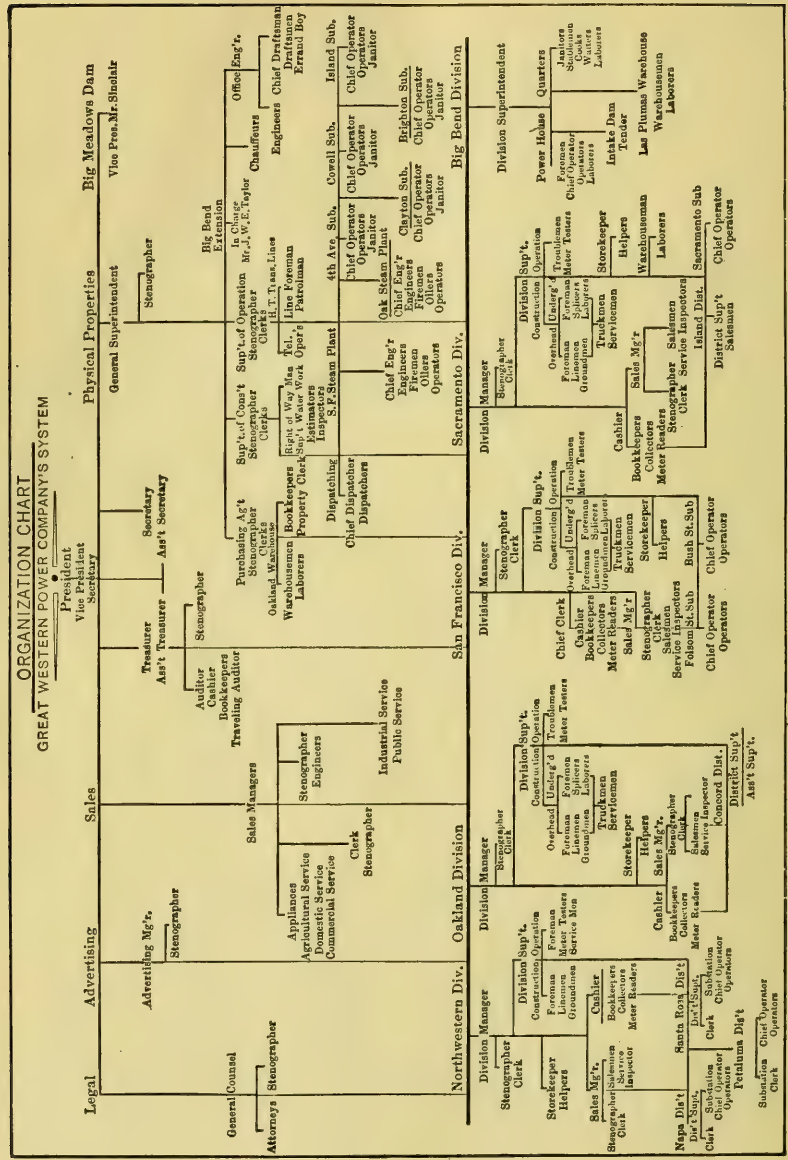
ORGANIZATION CHART
GREAT WESTERN POWER COMPANY'S SYSTEM
President
Vice President
Secretary
Legal
Advertising
Sales
Physical Properties
Big Meadows Dam
Vice Pres. Mr. Sinclair
General Counsel
Attorneys
Stenographer
Advertising Mg'r.
Stenographer
Sales Managers
Appliances
Agricultural Service
Domestic Service
Commercial Service
Clerk
Stenographer
Stenographer
Engineers
Industrial Service
Public Service
Treasurer
Ass't Treasurer
Auditor
Cashier
Bookkeepers
Traveling Auditor
Stenographer
Secretary
Ass't Secretary
General Superintendent
Stenographer
Purchasing Ag't
Stenographer
Clerks
Oakland Warehouse
Warehousemen
Laborers
Bookkeepers
Property Clerk
Sup't. of Cons't
Stenographer
Clerks
Right of Way Man
Sup't Water Work
Estimators
Inspectors
Sup't. of Operation
Stenographer
Clerks
H. T. Trans. Lines
Tel. Opers
Line Foreman
Patrolman
Big Bend Extension
In Charge Mr. J. W. E. Taylor
Chauffeurs
Office Eng'r.
Engineers
Chief Draftsman
Draftsmen
Errand Boy
Dispatching
Chief Dispatcher
Dispatchers
S. F. Steam Plant
Chief Eng'r
Engineers
Firemen
Oilers
Operators
Oak Steam Plant
Chief Eng'r
Engineers
Firemen
Oilers
Operators
4th Ave. Sub.
Chief Operator
Operators
Janitor
Cowell Sub.
Chief Operator
Operators
Janitor
Island Sub.
Chief Operator
Operators
Janitor
Clayton Sub.
Chief Operator
Operators
Janitor
Brighton Sub.
Chief Operator
Operators
Janitor
Northwestern Div.
Oakland Division
San Francisco Div.
Sacramento Div.
Big Bend Division
Division Manager
Stenographer
Clerk
Division Sup't.
Construction
Operation
Overhead
Underg'd
Foreman
Linemen
Groundmen
Foremen
Splicers
Laborers
Troublemen
Meter Testers
Service Men
Truckmen
Servicemen
Storekeeper
Helpers
Sales Mg'r.
Salesmen
Service Inspector
Cashier
Bookkeepers
Collectors
Meter Readers
Chief Clerk
Santa Rosa Dist't
Napa Dis't
Petaluma Dis't
Dis't Supt.
Clerk
Substation
Chief Operator
Operators
Concord Dist.
District Sup't.
Ass't Sup't.
Folsom St. Sub
Bush St. Sub
Island Dist.
District Sup't
Salesmen
Sacramento Sub
Warehouseman
Laborers
Division Superintendent
Power House
Foremen
Chief Operator
Operators
Laborers
Quarters
Janitors
Stablemen
Cooks
Waiters
Laborers
Intake Dam Tender
Las Plumas Warehouse
Warehousemen
Laborers

FIG. 435

is able to keep close watch on the conditions and make changes in load generation, voltage, frequency, gate openings, etc., in order to obtain the most satisfactory and efficient operation.

The real value of a load despatcher looms up under abnormal or trouble conditions. When trouble affects the system it is instantly apparent on the recording instruments. The system operator immediately gets into communication with the station affected and, in case of transmission line trouble, learns what switches have opened and then, if possible, gives orders to cut over to duplicate lines. The faulty line receives one or two trials, either at full voltage or by bringing the voltage up slowly on separate generators. If the short or trouble still shows up on the line ammeters, the line is cut up into sections, according to the judgment of the system operator, and tried until the faulty section is located. Patrolmen and repair men, who are on constant call, then receive directions for making the repairs. Trouble on the distribution system, as, for instance, where a feeder will not stay in, owing to a short on the line, it is immediately reported and turned over to the line department, which looks after the repairing of the line. In case of trouble with the underground system, the system operator supervises the locating and disconnecting of the faulty feeder and then notifies the underground department, whose business it is to repair the trouble. In case of trouble of a serious nature, the heads of the departments affected are notified and take active charge of the situation.

The organization of the operating force of a hydro-electric generating station is necessarily less complicated than in a steam station. It is determined largely by the location and the arrangement, and there are so many different conditions in such systems that it is impossible to recommend any exact form of organization, as really no two can be quite alike. If the station is not too large, it is desirable to have the hydraulic superintendent report to the station superintendent; but if the development is of such a magnitude as to require the entire time of a superintendent for each of the departments under consideration, a position is warranted for a man to whom both electric and hydraulic superintendents will report, thus still bringing the responsibility of operation of the two departments under one head.

It is a general practice to maintain one man at all times on each of the different levels or floors of the power-house, such as the switchboard gallery, the main floor and the basement, where with vertical units the turbines proper, as well as the oil pumps and other auxiliaries are located. The man in the basement could, in all probability, be dispensed with in plants using horizontal units. In addition to these men, a chief operator should be provided for each shift, whose

duties should carry him to all parts of the building. For a very large station the above force may be entirely inadequate, and for small plants the force may be reduced.

The switching operations are determined by the general method of operation. It is desirable to eliminate all high-tension switching under load, because such switching may set up surges which may discharge into the transformers and cause resonance, resulting in internal disturbances in the same. When a line is to be cut into service, the high-tension switches in the main and sub-station should be closed first, then the low-tension transformer switch in the generating station should be closed, energizing the transformers and the line, after which the low-tension transformer switch in the sub-station is closed and the load picked up. In case it becomes necessary to open a high-tension switch in a loaded line, the circuit should, if possible, first be parallel with another before opening the switch. If, on the other hand, transformers are to be paralleled on both high- and low-tension sides, the low-tension switch should be closed first, assuming that the low-tension bus is energized. Similarly, in cutting out the transformer the low-tension switch should be opened last.

Operating Records. One of the essential things in connection with the operation of hydro-electric generating stations is the keeping of accurate records. Record sheets should contain only the most important readings, as with complicated forms the attendant generally realizes that a large number of the readings are of no importance and for this reason be becomes very lax in his attention to the readings in general, and as a consequence the important ones may suffer. The following description applies to an actual record sheet for a medium-size station (Fig. 436), which has been found to give satisfactory results. The sheet is of the size of ordinary letter paper and is ruled for hourly records of "Water," "Main Units," "Cycles," "Power-factor," "Exciters," "Transformers and Floodgates." These items are listed vertically and the sheet is divided into 24 vertical columns, one for each hour. At the top are given the "Forebay" readings and "Tailrace" readings, the difference between which gives the "Effective Head." Immediately below are listed the indicated kilowatts and per cent gate opening of each generator in service, following which are given the "Total Indicated Kilowatts" and "Total Per Cent Gate." The total kilowatt hours during each hour, as read from the watt-hour meters, is plotted as a block curve extending across the face of the sheet.

This serves as a better record for the actual station output than the indicated kilowatts. It has been found necessary, however, to follow the indicated kilowatts to serve as a check on the efficiency and condition

of the units in general, from time to time, as well as to determine what capacity would be required for short interval peaks. The station voltage is also plotted as a block curve across the face of the sheet.

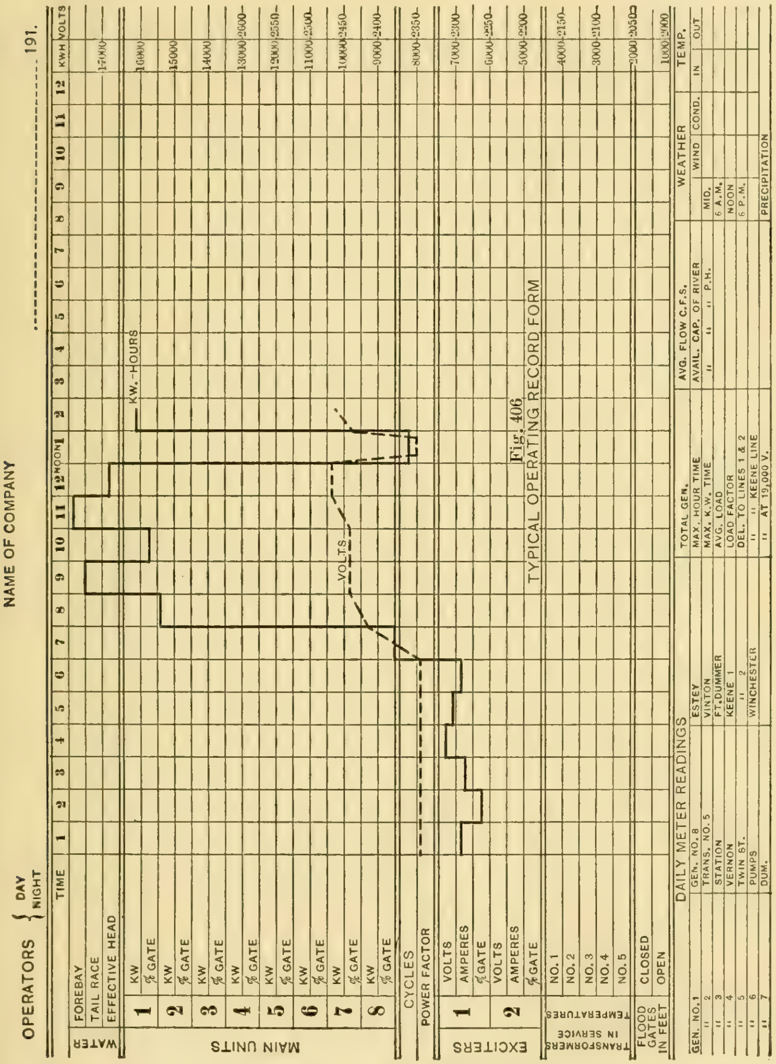

FIG. 436.—Typical Form for Operating Record.

The exciters form an individual group, and for each exciter the voltage current and per cent gate opening are recorded.

Transformer records are limited to the temperatures. These are taken hourly, and at the same time the oil elevation is noted but not

recorded. If the transformer is not in service the column in which the temperature is listed is left blank. If in service, the temperature is taken and recorded.

Under the item, "Floodgates" the total opening of the floodgates in feet is recorded, rather than each one separately. This record is maintained daily, the flow of the river at each of the stations being followed very closely.

At the bottom of the sheet appear the daily readings of the various generator and feeder watt-hour meters taken at midnight of each twenty-four hours. The following items are also recorded at the bottom of the sheet: "Total Generated," or the total output of the station for twenty-four hours; the "Maximum Hour Time," or the maximum kw. hr. of any particular hour during the day; the "Maximum kw. Time," or the maximum indicated kilowatts at any particular instant; the "Average Load," obtained by dividing the total kilowatt hours generated by 24; the "Load Factor," obtained by dividing the "Average Load" by the "Max. kw. Time"; the "Average Flow of the River in Cubic Feet per Second," calculated each day and converted into "Available Capacity of River," which is shown in kw. hr.; the "Available Capacity of Power House," shown in kw. hr., and determined by calculating the capacity of the machines under the average head for twenty-four hours; the "Kw. hr. Lost," or the difference between what was actually generated by the machines and what could have been secured from the river during the same number of hours.

Any important notes of operation are entered on the back of each day's log sheet. These notes, together with certain records for log sheets, are also entered each day in a log book kept on the operator's desk at all times for reference purposes. Weather conditions and temperatures are recorded four times daily, at midnight, 6 a.m., noon, and 6 p.m. A rain gauge is provided on the roof of the station from which records of precipitation covering each twenty-four hours are obtained.

A record form of a large power system in the West is shown in Fig. 437.

Operating and Maintenance Instructions. Several of the larger hydro-electric companies have developed very successful methods of systematizing the operating details and properly training the operating force, thus obtaining a considerable improvement over the methods ordinarily in use. A description of the practice by one of the larger hydro-electric companies, as given in the 1917 Report of the N.E.L.A. Committee on Prime Movers, should therefore be of interest.

Operating Instructions. The operation of the plant is covered by

DAILY STATION LOG

.... STATION FOR .... 191....

GENERATION

Time	...... GENERATOR					...... GENERATOR					...... GENERATOR					...... GENERATOR					...... GENERATOR					ENTIRE STATION			Time
			HEAD IN FEET					HEAD IN FEET					HEAD IN FEET					HEAD IN FEET					HEAD IN FEET						
	Actual Amperes (Av. of 3 Phases)	Kilowatts	Pressure	Vacuum	Total	Actual Amperes (Av. of 3 Phases)	Kilowatts	Pressure	Vacuum	Total	Actual Amperes (Av. of 3 Phases)	Kilowatts	Pressure	Vacuum	Total	Actual Amperes (Av. of 3 Phases)	Kilowatts	Pressure	Vacuum	Total	Actual Amperes (Av. of 3 Phases)	Kilowatts	Pressure	Vacuum	Total	Actual Amperes (Av. of 3 Phases)	Kilowatts	Power Factor %	
M'd't																													M'd't
1																													1
2																													2
3																													3
4																													4
5																													5
6																													6
7																													7
8																													8
9																													9
10																													10
11																													11
Noon																													Noon
1																													1
2																													2
3																													3
4																													4
5																													5
6																													6
7																													7
8																													8
9																													9
10																													10
11																													11
M'd't																													M'd't
			Total Average					Total Average					Total Average					Total Average					Total Average			Peak		Total Average	

INTEGRATING METER READINGS

	GENERATORS							TO TRANSMISSION SYSTEM						TO LOCAL DISTRIBUTING SUB STATION			STATION USE
Circuit	...... Gen.	...... Gen.	...... Gen.	...... Gen.	...... Gen.	Total as Shown by Gen. Meters	Totalizing Meter	...... Circuit	...... Circuit	...... Circuit	...... Circuit	Total as Shown by Circuit Meters	Totalizing Meter	...... Circuit	...... Circuit	Total	......
Midnight Today																	
Midnight Yesterday																	
Kw.H.																	

GENERAL DATA

LOAD DATA			PRECIPITATION		
Peak Load	Kw.		Rainfall	Inches	
Load Factor	%		Snowfall	"	
Average Load	Kw.		Total equivalent rainfall	"	
Continuous load available	"				

STREAM DISCHARGE					WHEEL DISCHARGE				
...... Gage Reading	A.M.	P.M.			...... Gage Reading	A.M.	P.M.		
			Max.	D.S.F.				Max.	D.S.F.
C.F.S.			Min.	"	C.F.S.			Min.	"
			Av.	"				Av.	"

AIR TEMPERATURE; HUMIDITY		
Max. Temp.	Deg. F.	
Min. "	"	
Av. "	"	
Humidity	%	

No. hrs. Wheels operated	...... Wheel	...... Wheel	...... Wheel	...... Wheel	...... Wheel	No. hrs. Station not operated account low water	Average head in feet on all Waterwheels	Weather

TIME AND NATURE OF SWITCHING AND UNUSUAL OCCURRENCES

SHIFT	...... M. to ...... M.	...... M. to ...... M.	...... M. to ...... M.
1st Operator			
2nd "			
3rd "			
4th "			

Station Superintendent

FIG. 437.

To face page 772.

instructions which not only express in writing what must be done in the case of certain emergencies, but also describe how the plant must be run under normal conditions.

These "Permanent Instructions," as they are called, are divided as follows:

General Station Rules, etc.
Safety Rules.
Electrical Operation—Normal and Abnormal.
Hydraulic Operation—Normal and Abnormal.
Duties of Operating Men.
Record and Forms.
Electrical Maintenance.
Hydraulic Maintenance.

The "General Station Rules" govern the employees as a body and are concerned with such things as wages, hours, leaves of absence, vacations, and miscellaneous matters regarding the conduct of the men in the stations.

Under "Safety Rules" come the usual regulations providing for the safety of the men working around electrical and mechanical equipment. Safety Rules also include rules for the "Hold-Off" system, by which the men are protected while working on apparatus.

Under the "Electrical Operating Instructions" are two divisions—normal and abnormal. The normal instructions deal with every-day conditions, and their aim is to specify how the apparatus shall be handled, what the connections shall be, and how the various other routine operations of the station shall be performed. The abnormal instructions are developed from cases of trouble that have been experienced in the station, and such as might occur. They include general instructions on handling trouble, instructions on various line complications and on generator, transformer, bus and oil switch trouble. They also include the handling of the station during lightning storms and low-water season operation, when particular attention must be paid to efficiency, as well as instructions for the flood season, and ice and sleet.

The "Hydraulic Operating" instructions are similarly divided into normal and abnormal.

The section on "Records and Forms" includes instructions on the use of the various forms, such as log sheets, graphic meter records, and also on record and tabulation work. The section on "Duties" specifies the particular duties of each operating attendant. The "Electrical and Hydraulic Maintenance" instructions cover such matters as the cleaning, inspection and repair of apparatus.

These instructions have been found very valuable in crystallizing the operation of the plant, making it more automatic and independent of the personal element. They have also made it considerably easier for those in charge to break in and instruct new men; under them all operators tend to do given things in the same way, a way which has been determined by study and experiment to be the best way. An attendant can be transferred from one shift to another without having to learn new methods. He will know that all operations, such as the starting and stopping of generators, handling of switches, etc., will be carried on in exactly the same way as on any other shift.

A good example of the result of study and system in operating methods is the comparatively simple matter of starting up a generator. Before the instructions were put into effect, the time for starting a unit would vary from $1\frac{1}{2}$ to 3 or 4 minutes, depending upon the individual operators and hydraulic attendants. A study was made of the various operations and the time taken to start a generator, and it was found that by having the several attendants do their work independently, without waiting for one another and without waiting for verbal instructions, operations could be performed simultaneously which were formerly done successively. It had been the practice for the governor man to make an inspection of the unit and for the operator to try out the oil switch, before the disconnectors were closed. These unnecessary precautions were eliminated by insisting that every unit and oil switch, in fact every part of the equipment, be ready for immediate service at any moment, unless it was covered by a "hold-off" tag. The operation of starting the unit on the governor also took time, and it is now the practice to start the unit on hand control. The best way of manipulating the gates to get the unit to accelerate more rapidly was observed, and the governor attendants instructed accordingly.

It has also been made the practice always to start the units quickly. The normal time now taken to start a unit is about sixty seconds. The record time on a stop-watch drill test was forty-one seconds, while in an actual emergency due to the loss of a steam turbine unit on the system, and resulting in frequency disturbance, a unit was paralleled and frequency brought to normal in thirty-five seconds after the disturbance occurred. In another case two units were paralleled and frequency brought to normal $1\frac{1}{2}$ minutes after the trouble.

An important feature of this quick starting is that it must accelerate very quickly at first and pass through the synchronous point very slowly. While the unit is accelerating the operator must send his assistant to close the disconnecting switches and have his synchronizing and voltmeter plugs in position before the unit comes up to speed, so

that as soon as the speed passes through the synchronous point he gets his "shot." If he misses the first "shot" there will be a delay of from fifteen to twenty seconds in bringing the speed back again; hence, it is important that the governor man manipulate the speed properly and be ready to take the first shot when it presents itself.

Another point is to have the field rheostat in the proper position for normal voltage, so that no time may be lost in manipulating the voltage. In cases of serious emergency, where there have already been interruptions to service or serious fluctuations of voltage, or where the hydroelectric plant has separated from the steam plant, the operator is instructed to parallel without the use of the synchroscope, in order to save time. In this case he opens the field of the incoming generator while closing its oil switch and immediately closes the field afterwards. Under the special conditions of high reactance of the units employed in the plant described, this results in a 5 to 8 per cent fluctuation in voltage in case the incoming unit (of approximately 10,000-kw. capacity) is 20 per cent less than the capacity already tied in on the bus.

Maintenance. The first task was to get up a machinery index wherein is listed the station apparatus. A letter size sheet, or several of them, are devoted to each piece of apparatus and upon these sheets are noted data or reference directions in regard to the apparatus, also references to a machinery repair log book, where may be obtained detailed information with regard to the repair history of the piece of apparatus.

In regard to the maintenance of the station, the operating attendants do a large amount of this work and practically all of the inspection. Instructions for cleaning and inspection have been very carefully drawn up, and the operating men instructed in the proper care of the apparatus. Every piece of apparatus in the station has been considered individually and it has been determined just how often it needs to be inspected and how thorough an inspection is needed. All the equipment is tabulated on charts, which show the periodicity of the inspections and provide spaces which are to be filled in with the date and initials of the attendant who made the inspection. These charts are posted on the wall in a conspicuous place and make an excellent graphical record of the status of the inspections of the entire station up to date. Any delayed inspections are, naturally, inquired into.

In addition to the current inspections by the operating men, there is also a more thorough inspection, made as often as may be necessary, but at less frequent intervals, by the electrical inspector and hydraulic inspector. The inspection work for these men also is laid out on schedule drawn up in the form of charts, and the date of inspection similarly

noted. This system of keeping track of inspections has been the result of much experimenting and investigation of the methods of other companies. The card index system, which is ordinarily used, does not have the advantage of immediate accessibility and becomes very bulky when each individual piece of apparatus in the station is included. An ordinary manifold note book is used for trouble reports; the original goes to the office to note that the inspection was made and later is placed on file. If the apparatus is found to be out of order a " Trouble Report " is made out on a regular form, space being provided for the report of the man who is to remedy the trouble, and also for further report or remarks from the *Electrical or Hydraulic Inspector.* In these remarks the inspector is supposed to give assurance that the trouble will not occur again, or state what is necessary to be done to prevent its recurrence. These reports are filed and later become valuable in eliminating troublesome features of design, when new apparatus is to be designed or purchased.

Assignment of Apparatus. Another thing which facilitates the inspection and cleanliness of the apparatus is the assignment of every particular piece of apparatus in the station to some particular person. Each attendant has his own particular apparatus for which he is responsible, which he must keep clean and in proper operating condition. When defects occur in this equipment he will either remedy them himself or report them on a " Trouble Report." If the apparatus is in bad condition it is this man whose attention is called to it, and if it is kept in exceptionally good condition it is he who receives the credit. An attendant who is inclined to be delinquent in attention to his apparatus soon finds that his equipment compares unfavorably with the adjacent equipment and will naturally remedy it without its having to be brought to his attention by his superior.

Exposed tool boards are mounted at different points in the station, so that attendants have available all they need in the way of tools for making such repairs as they are able to take care of without the assistance of the regular maintenance department. By being permitted to repair their own apparatus, the operating attendants become more familiar with its details and learn better how to operate it and take operating care of it, and are given an interesting occupation, in addition to saving the time of the maintenance men in attending to minor repairs.

The aim is to substitute preventive maintenance for breaking down repairs. The result of this inspection and maintenance system has been that the apparatus is kept in better condition, and this has been accomplished with the minimum of attention on the part of

superiors, as the system is more or less automatic in its workings. At the same time, the reports and schedules give the superior very definite knowledge of the condition of his equipment. As all this work is laid out before the man in the form of instructions, the superior is relieved of the necessity of continually correcting new men and instructing them in the proper methods of doing things. This system also eliminates dependence on word-of-mouth transmission of instructions from one man to another.

When the work is thus systematized, the possibility of neglect of maintenance work on apparatus is minimized. Moreover, when work is so scheduled, as to time, that planning is required in order to finish it in the time allotted, there is less time lost between jobs and in doing the maintenance jobs, and the maintenance or operating shifts are thus able to turn out more work and better work.

APPENDIX I

PRINCIPAL SYSTEMS AND THEIR "NORMAL SYSTEM OR CIRCUIT VOLTAGES," 66,000 VOLTS AND ABOVE *

These "Normal System or Circuit Voltages" are on the basis of the highest rated *Secondary* Voltage of Transformers supplying these systems or circuits.

No.	Normal System or Circuit Voltage.	Altitude of Stations in Feet.	Frequency in Cycles per Second.	Neutral Ground.	Operating Company.	Beginning of Operation.
1	66,000	4000–6000	60		Montana Power Co.	
2	66,000				Parr Shoals Pr. Co.—S. Carolina	
3	66,000	600–1000	60		Central Pr. Co.—Ohio	
4	66,000	600–1000	60		Central Pr. Co.—Wellsburgh, W. Va.	
5	66,000	350– 950	60		Columbus Pr. Co.—Georgia	
6	66,000				Indiana General Service Co.	
7	66,000	1200	60	Dir.	San Joaquin Lt. & Pr. Co.—Calif.	
8	66,000	350	60		Central Georgia Pr. Co.	
9	66,000	100– 250	60	Dir.	Turners Fall Pr. & Elec. Co.	
10	66,000	500	60		Keene Gas & Elec. Co.—N. H.	
11	66,000		60		Pacific Pr. & Lt. Co.—Oregon	
12	66,000		60		Tennessee Pr. Company	
13	66,000	100	60		Eastern Connecticut Pr. Co.	
14	66,000	100	60	Dir.	Connecticut Lt. & Pr. Co.	
15	66,000		60		Connecticut Power Co.	
16	66,000	200	60		Fall River Elec. Lt. Co.	
17	66,000	500	60		Narragansett Elec. Lt. Co.	
18	66,000	850	60		Wisconsin-Minnesota Lt. & Pr. Co.	
19	66,000	1200	25–60	No	Great Northern Pr. Co.—Minnesota	
20	66,000				American Falls Pr. Co.—Idaho	
22	66,000		60		New Hampshire Water & Elec. Lt. Co.	
23	66,000		60		Northwestern Elec. Co.—Oregon	
24	66,000		60		North Coast Pr. Co.—Oregon	
25	66,000				Wisconsin Pr. & Lt. Co.	
26	66,000		60		Idaho Pr. Co.	
27	66,000		60		San Diego Gas & Elec. Co.	
28	66,000		25		N. Y., N. H. & H. R. R.	
29	66,000		60		Duquesne Lt. Co.	
30	66,000				Wisconsin River Pr. Co.	
31	66,000				Steubenville & E. Liverpool Rwys. Co.	
32	66,000				Monongahela Valley Traction Co.	
33	66,000				Philadelphia Electric Co.	
34	67,560		60		Braden Copper Co.	
35	69,000				Albany & Southern Railroad	
36	69,000				Kingston Gas & Elec. Co.	

Dir. = Direct. Res. = Resistance.

* From article on "Present Status of High Voltage Transmission of Power." By W. W. Levis. General Electric Review, October, 1922.

PRINCIPAL SYSTEMS AND THEIR "NORMAL SYSTEM OR CIRCUIT VOLTAGES," 66,000 VOLTS AND ABOVE—*Continued*

No.	Normal System or Circuit Voltage.	Altitude of Stations in Feet.	Frequency in Cycles per Second.	Neutral Ground.	Operating Company.	Beginning of Operation.
37	69,000				Central Hudson Gas & Elec. Co.	
38	70,000	100	50	Res.	Royal Water Falls Adm. Alfkarleby Development—Sweden	1915
39	70,000	1000–2000	25	No	Loussavaarda Kirunvaara Aktiebalag—Sweden	
40	70,000	1000–2000	25	No	Swedish State Rwys. Projus Dev.	1914
41	70,000	1000–3000	50	No	Guadalajara—Mexico	1911
42	70,000	0– 500	25	Res.	Penn Water & Pr. Co.	1910
43	70,000	0–1000	50	Res.	Societa Electrica Rivera Di Ponente—Spain	1911
44	70,000	0–1000	50	No	Hydroelectrica Espanola Molinar—Spain	1910
45	72,000		60		Peninsular Pr. Co.	
46	72,000	600	30		Consumers Pr. Co.	1906
47	72,000		60		City of Winnipeg	1911
48	72,000	500–2000	42	No	Societa Generale Electrica Del 'Adamella—Italy	1910
49	72,000	500–1000	42	Res.	City of Milan—Italy	1910
50	72,000	0– 500	60	Dir.	New England Power Co.	1909
51	72,000	200	50	Dir.	So. Cal. Ed. Co. (Los Angeles Dist.)	1905
52	75,000	2700	50–60	Dir.	So. Cal. Ed. Co. (Kern River 3 Dev.)	1921
53	75,000	2700	50–60	Dir.	So. Cal. Ed. Co. (Kern River 1 Dev.)	1907
54	76,200	600	25		Milwaukee Elec. Rwy. & Lt. Co.	1909
55	77,000				Monviso Calcinere—Italy	
56	77,000		60		Nagoya Elec. Lt. Co.—Japan	
57	77,000	0–1000	50	Res.	Katsuragawa Hydro-Elec. Co.—Japan	1912
58	77,000	Below 4000	60	Res.	Kiso Denki Kogyo K.K.—Japan (Daido Denryoku)	
59	80,000	3100	25	No	Govt. of Mysore—India	1921
60	80,000	1000–2000	15	Res.	Swedish State Rwys. Projus Dev.	1915
61	80,000		60		St. Lawrence Trans. Co.	1915
62	80,000	300	60	No	Northern Pr. Co. (N. Y.)	
63	80,000	300	60	No	Hannawa Falls Pr. Co.	
64	80,000	300	60	No	Raquette River Paper Co.	
65	80,000		60		Ogdensburgh Paper Mills, Inc.	
66	80,000		60		Remington Paper Co.	
67	80,000		60		De Grasse Paper Co.	
68	85,000	2250–10000	50	Dir.	Mexican Lt. & Pr. Co.	1910
69	86,500	300– 750	25	No	Toronto Pr. Co.	1914
70	87,000	1000–4500	60	No	Southern Sierras Pr. Co.	1915
71	88,000	1000	50	Res.	Victoria Falls & Transvaal Pr. Co.—South Africa	1913
72	88,000		50	Dir.	Tasmania Hydro-Elect. & Metal Co.	
73	88,000	2180	60	No	Cia. Paulista de Estradas de Ferro—Brazil (Paulista Rwys.)	1921
74	88,000	0–1000	60	No	Sao Paulo Elec. Co.—Brazil	1914
75	88,000	0–1000	50	No	Rio Janeiro T. L. & Pr. Co.—Brazil	1913
76	88,000	1000–2500	60	No	Appalachian Power Co.	1912
77	88,000	0– 500	42	No	Societa Italiana di Elettrochimica—Italy	1912
78	88,000	1000–2500	60	Dir.	Ky. & W. Va. Pr. Co.	1920

PRINCIPAL SYSTEMS AND THEIR "NORMAL SYSTEM OR CIRCUIT VOLTAGES," 66,000 VOLTS AND ABOVE—*Continued*

No.	Normal System or Circuit Voltage.	Altitude of Stations in Feet.	Frequency in Cycles per Second.	Neutral Ground.	Operating Company.	Beginning of Operation.
79	88,000	1000–2500	60	No	Lynchburg Trac. Co.	1920
80	90,000	0–1000	50	No	Energia Electrica De Cataluna—Spain	1914
81	100,000	100	25	Res.	City of Stockholm Electricity Works—Sweden, Untra Development	1917
82	100,000	2750–7500	60	Dir.	Pueblo Tramways Lt. & Pr.—Mexico	
83	100,000	100– 300	60	Dir.	Shawinigan Water & Pr. Co.	1912
84	100,000	0–1000	50	No.	Tata Hydro Elec. Pr. Co.—India	1914
85	100,000	0–1000	50	Dir.	Andhra Val. Elec. Pr. Supply Co.—India	1921
86	100,000	5000–10500	60	No	Colorado Power Co.	1909
87	100,000	0– 500	60	No	Great Western Power Co.	1909
88	102,000	4000–6000	50	Dir.	Montana Pr. Co.	1910
89	102,000	3300–5500	60	Dir.	Great Falls Pr. Co.	
90	102,000	3300–5500	60	Dir.	Anaconda Copper Mining Co.	
91	102,000	4000–6000	60	Dir.	Thompson Falls Pr. Co.	
92	102,000	5000	60	Dir.	C. M. & St. P. R. R. (Eastern Electrification)	1915
93	103,900	100– 400	60	Dir.	Yadkin River Pr. Co.	1912
94	103,900	100– 500	60	Dir.	Carolina Pr. & Lt. Co.	
95	103,900	100– 400	60	Dir.	Palmetto Pr. & Lt. Co.	
96	104,000	0–2000	60	Dir.	Sierra & San Francisco Pr. Co. (Oper. by P. G. & E. Co.)	1910
97	104,000	4000–6000	60	No	Truckee River G. E. Co.	
98	110,000	200–2100	50	Dir.	City of Los Angeles	1914
99	110,000	400– 850	60	Dir.	Southern Power Co.	1909
100	110,000	0–4000	60	Dir.	C. M. & St. P. R. R. (Western Elec.)	1920
101	110,000	0– 600	60	Dir.	Puget Sound T. Lt. & Pr. Co.	1920
102	110,000	2000–4000	60	Dir.	Washington Water Pr. Co.	1920
103	110,000	0– 500	60	Dir.	New England Pr. Co.	Not yet
104	110,000	0–9000	50	Dir.	Chile Exploration Co.	1915
105	110,000	0–4000	50	Dir.	Compania Nacional De Fuerza—Chile	
106	110,000	0–6000	50	Dir.	Chilian El. Tram. Lt. & Pr. Co.	
107	110,000	0–3000	50	Dir.	Ebro Irrigation & Pr. Co.—Spain	1914
108	110,000	5500	60		Cia. Agricola y Fuerza Electrico del Rio Conchas—Mexico	
109	110,000	2000–3000	60	Res.	Mexican Northern Pr. Co.	1914
110	110,000	0– 100	60	Dir.	Virginia Rwy. & Pr. Co.	1919
111	110,000	300	60	No	Aluminum Co. of Amer. (Massena Development)	1914
112	110,000	300	60	No	Cedar Rapids Mfg. & Pr. Co.	1914
113	110,000	1000	25	Res.	Lehigh Navigation Elec. Co.	1914
114	110,000	500	25	Dir.	Union Elect. Lt. & Pr. Co.—St. Louis	1913
115	110,000	460– 530	25	Dir.	Mississippi River Pr. Co.	1913
116	110,000	500– 600	60	Dir.	Air Nitrates Corp.—Govt. Plant No. 2	1918
117	110,000	200– 800	60	Dir.	Alabama Power Company	1913
118	110,000	600–1600	60	Res.	Georgia Rwy. & Pr. Co.	1912
119	110,000	500	50	No	Lauchhammer A. G.—Germany	1911
120	110,000	600	25	Res.	Hamilton Hydro. Elec. System	1910
121	110,000	600	25	Res.	Hydro Elect. Pr. Comm. of Ontario	1910
122	115,000	0–2500	50	No	Inawashiro Hydro Elec. Pr. Co.	1914

PRINCIPAL SYSTEMS AND THEIR "NORMAL SYSTEM OR CIRCUIT VOLTAGES," 66,000 VOLTS AND ABOVE—*Continued*

No.	Normal System or Circuit Voltage.	Altitude of Stations in Feet.	Frequency in Cycles per Second.	Neutral Ground.	Operating Company.	Beginning of Operation.
123	115,000	350– 900	60	No	Columbus Pr. Co.	1913
124	120,000	500	60	Dir.	Minneapolis G. E. Co.	1917
125	120,000	800	60	Dir.	Wis.-Minn. Lt. & Pr. Co.	1917
126	120,000	800	60		Northern States Power Co.	1917
127	120,000	500– 900	60	No	Tennessee Power Co.	1914
128	120,000	500– 900	60	No	Chattanooga & Tennessee River Power Co.	1914
129	120,000	500– 900	60	No	Knoxville Rwy. & Lt. Co.	1921
130	120,000	600–1000	60		West Penn Power Co.	
131	120,000	100	50	Petersen Reactor	Royal Water Falls Adm. Trollhatten, Sweden (Westeras Tie Line)	1922
132	120,000	Below 4000	50	Dir.	Basse Isere—France	
133	120,000	3300	50	Dir.	Compagnie des Chemins de Fer du Midi —France	
134	125,000	0–4500	60	Dir.	Pacific Gas & Electric Co.	1920
135	127,000	665	60	Dir.	San Joaquin Lt. & Pr. Corp.	1920
136	130,000	4000–6000	60	Dir.	Utah Pr. & Lt. Co.	1914
137	130,000	0–3000	50	Petersen Reactor	Catalana de Gas y Electricidad Cia—Spain	
138	130,000	0–2000	50	Dir.	Sociedad Anonima Electra del Lima—Portugal	
139	132,000	2000	50	Dir.	Hidroelectrica Espagnola Salto dos Aguas Rio Jugas—Spain	
140	132,000	0–3000	50	Dir.	Soc. Anonima Hydro. Iberica—Spain	
141	132,000	600	25	Res.	Hydro-Elec. Pr. Com. Ont. (Queenston Development)	1923
142	132,000	Below 4000	50	Dir.	Victorian Electricity Comm., Melbourne —Australia	1922
143	132,000	600–1000	60	Dir.	Amer. Gas & Electric Co.	1917
144	132,000	600–1000	60	Dir.	Northern Ohio Pr. & Lt. Co.	
145	132,000	600–1000	60	Dir.	Ohio Power Co.	
146	132,000	600–1000	60	Dir.	West Penn Power Co.	
147	140,000	5000	60	No	Nevada-California Pr. Co.	Not yet
148	140,000	750	30 60	No	Consumers Power Co.	1918 1912
149	140,000	1000–4500	60	No	Southern Sierras Power Co.	1920
150	150,000	0–5000	50	Dir.	Southern California Edison Co.	1913
151	150,000	1000	60	Dir.	Aluminum Co. of America (Tallassee Development)	1919
152	154,000	Below 4000	60	Res.	Taiwan Denryoku K.K.—Formosa	1923
153	154,000	Below 4000	50	Res.	Shinyetsu Denryoku K.K.—Japan	1923
154	154,000	Below 5000	50	Res.	Keihin Denryoku K.K.—Japan	1923
155	154,000		50	Res.	Tokyo Elec. Lt. Co.—Japan	1923
156	154,000	Below 4000	60	Res.	Nippon Elec. Pr. Co.—Japan	1923
157	154,000	Below 4000	60	Res.	Daido Denryoku—Japan	1923
158	165,000	0–3000	60	Dir.	Great Western Power Co.	1923
159	220,000	0–5000	50	Dir.	Southern California Edison Co.	1923
160	220,000	0–4500	60	Dir.	Pacific Gas & Electric Co.	1923

APPENDIX II

TEXT OF THE FEDERAL WATER-POWER ACT

(Became law, June 11, 1920)

An Act

To create a Federal Power Commission and to define its powers and duties, to provide for the improvement of navigation, for the development of water power, for the use of lands of the United States in relation thereto, to repeal Section 18 of " An act making appropriations for the construction, repair and preservation of certain public works on rivers and harbors, and for other purposes," approved Aug. 8, 1917, and for other purposes.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled, That a commission is hereby created and established, to be known as the Federal Power Commission (hereinafter referred to as the commission), which shall be composed of the Secretary of War, the Secretary of the Interior and the Secretary of Agriculture. Two members of the commission shall constitute a quorum for the transaction of business, and the commission shall have an official seal, which shall be judicially noticed. The President shall designate the chairman of the commission.

The Executive Secretary

Sec. 2. That the commission shall appoint an executive secretary, who shall receive a salary of $5,000 a year, and prescribe his duties, and the commission may request the President of the United States to detail an officer from the United States Engineer Corps to serve the commission as engineer officer, his duties to be prescribed by the commission. The work of the commission shall be performed by and through the Departments of War, Interior and Agriculture, and their engineering, technical, clerical and other personnel, except as may be otherwise provided by law.

All of the expenses of the commission, including rent in the District of Columbia, all necessary expenses for transportation and subsistence, including, in the discretion of the commission, a per diem of not exceeding $4 in lieu of subsistence incurred by its employees under its orders in making any investigation, or conducting field work, or upon official business outside of the District of Columbia and away from their designated points of duty, shall be allowed and paid on the presentation of itemized vouchers therefor approved by a member or officer of the commission duly authorized for that purpose; and in order to defray the expenses made necessary by the provisions of this act there is hereby authorized to be appropriated such sums as Congress may hereafter determine, and the sum of $100,000 is hereby appropriated, out of any moneys in the Treasury not otherwise appropriated, available until expended, to be paid out upon warrants drawn on the Secretary of the Treasury upon order of the commission.

Definition of Terms

Sec. 3. That the words defined in this section shall have the following meanings for the purposes of this act, to wit:

" Public lands " means such lands and interest in lands owned by the United States as are subject to private appropriation and disposal under public-land laws. It shall not include " reservations," as hereinafter defined.

" Reservations " means national monuments, national parks, national forests, tribal lands embraced within Indian reservations, military reservations and other lands and interests in lands owned by the United States, and withdrawn, reserved or withheld from private appropriation and disposal under the public-land laws; also lands and interests in lands acquired and held for any public purpose.

" Corporation " means a corporation organized under the laws of any state or of the United States empowered to develop, transmit, distribute, sell, lease or utilize power in addition to such other powers as it may possess and authorized to transact in the state or states in which its project is located all business necessary to effect the purpose of a license under this act. It shall not include " municipalities " as hereinafter defined.

" State " means a state admitted to the Union, the District of Columbia and any organized Territory of the United States.

" Municipality " means a city, county, irrigation district, drainage district or other political subdivision or agency of a state competent under the laws thereof to carry on the business of developing, transmitting, utilizing or distributing power.

" Navigable waters " means those parts of streams or other bodies of water over which Congress has jurisdiction under its authority to regulate commerce with foreign nations and among the several states, and which either in their natural or improved condition, notwithstanding interruptions between the navigable parts of such streams or waters by falls, shallows or rapids compelling land carriage, are used or suitable for use for the transportation of persons or property in interstate or foreign commerce, including therein all such interrupting falls, shallows or rapids; together with such other parts of streams as shall have been authorized by Congress for improvement by the United States or shall have been recommended to Congress for such improvement after investigation under its authority.

" Municipal purposes " means and includes all purposes within municipal powers as defined by the constitution or laws of the state or by the charter of the municipality.

" Government dam " means a dam or other work, constructed or owned by the United States for government purposes, with or without contribution from others.

" Project " means complete unit of improvement or development, consisting of a power house, all water conduits, all dams and appurtenant works and structures (including navigation structures) which are a part of said unit, and all storage, diverting or forebay reservoirs directly connected therewith, the primary line or lines transmitting power therefrom to the point of junction with the distribution system or with the interconnected primary transmission system, all miscellaneous structures used and useful in connection with said unit or any part thereof, and all water rights, rights-of-way, ditches, dams, reservoirs, lands or interest in lands the use and occupancy of which are necessary or appropriate in the maintenance and operation of such unit.

" Project works " means the physical structures of a project.

" Net investment " in a project means the actual legitimate original cost thereof as defined and interpreted in the " classification of investment in road and equip-

ment of steam roads, issue of 1914, Interstate Commerce Commission," plus similar costs of additions thereto and betterments thereof, minus the sum of the following items properly allocated thereto, if and to the extent that such items have been accumulated during the period of the license from earnings in excess of a fair return on such investment: (*a*) Unappropriated surplus, (*b*) aggregate credit balances of current depreciation accounts, and (*c*) aggregate appropriations of surplus or income held in amortization, sinking fund or similar reserves, or expended for additions or betterments or used for the purposes for which such reserves were created. The term " cost " shall include, in so far as applicable, the elements thereof prescribed in said classification, but shall not include expenditures from funds obtained through donations by states, municipalities, individuals or others, and said classification of investment of the Interstate Commerce Commission shall in so far as applicable be published and promulgated as a part of the rules and regulations of the commission.

Powers of the Commission

Sec. 4. That the commission is hereby authorized and empowered—

(*a*) To make investigations and to collect and record data concerning the utilization of the water resources of any region to be developed, the water-power industry and its relation to other industries and to interstate or foreign commerce, and concerning the location, capacity, development costs and relation to markets of power sites, and whether the power from government dams can be advantageously used by the United States for its public purposes, and what is a fair value of such power, to the extent the commission may deem necessary or useful for the purposes of this act. In order to aid the commission in determining the net investment of a licensee in any project, the licensee shall, upon oath, within a reasonable period of time, to be fixed by the commission, after the construction of the original project or any addition thereto or betterment thereof, file with the commission, in such detail as the commission may require, a statement in duplicate showing the actual legitimate cost of construction of such project, addition or betterment, and the price paid for water rights, rights-of-way, lands or interest in lands. The commission shall deposit one of said statements with the Secretary of the Treasury. The licensee shall grant to the commission or to its duly authorized agent or agents, at all reasonable times, free access to such project, addition or betterment, and to all maps, profiles, contracts, reports of engineers, accounts, books, records and all other papers and documents relating thereto.

(*b*) To co-operate with the executive departments and other agencies of state or national governments in such investigations; and for such purpose the several departments and agencies of the national government are authorized and directed upon the request of the commission, to furnish such records, papers and information in their possession as may be requested by the commission, and temporarily to detail to the commission such officers or experts as may be necessary in such investigations.

(*c*) To make public from time to time the information secured hereunder, and to provide for the publication of its reports and investigations in such form and manner as may be best adapted for public information and use. The commission, on or before the first Monday in December of each year, shall submit to Congress for the fiscal year preceding a classified report showing the permits and licenses issued under this act, and in each case the parties thereto, the terms prescribed and the moneys received, if any, on account thereof.

(*d*) To issue licenses to citizens of the United States or to any association of such

citizens, or to any corporation organized under the laws of the United States or any state thereof, or to any state or municipality, for the purpose of constructing, operating and maintaining dams, water conduits, reservoirs, power houses, transmission lines or other project works necessary or convenient for the development and improvement of navigation, and for the development, transmission and utilization of power across, along, from or in any of the navigable waters of the United States, or upon any part of the public lands and reservations of the United States (including the Territories), or for the purpose of utilizing the surplus water or water power from any government dam, except as herein provided: Provided, that licenses shall be issued within any reservation only after a finding by the commission that the license will not interfere or be inconsistent with the purpose for which such reservation was created or acquired, and shall be subject to and contain such conditions as the Secretary of the department under whose supervision such reservation falls shall deem necessary for the adequate protection and utilization of such reservation: Provided, further, that no license affecting the navigable capacity of any navigable waters of the United States shall be issued until the plans of the dam or other structures affecting navigation have been approved by the Chief of Engineers and the Secretary of War. Whenever the contemplated improvement is, in the judgment of the commission, desirable and justified in the public interest for the purpose of improving or developing a waterway or waterways for the use or benefit of interstate or foreign commerce, a finding to that effect shall be made by the commission and shall become a part of the records of the commission: Provided further, that in case the commission shall find that any government dam may be advantageously used by the United States for public purposes in addition to navigation, no license therefor shall be issued until two years after it shall have reported to Congress the facts and conditions relating thereto, except that this provision shall not apply to any government dam constructed prior to the passage of this act: And provided further that upon the filing of any application for a license which has not been preceded by a preliminary permit under subsection (*e*) of this section, notice shall be given and published as required by the proviso of said subsection.

(*e*) To issue preliminary permits for the purpose of enabling applicants for a license hereunder to secure the data and to perform the acts required by Section 9 hereof: Provided, however, that upon the filing of any application for a preliminary permit by any person, association or corporation the commission, before granting such application, shall at once give notice of such application in writing to any state or municipality likely to be interested in or affected by such application, and shall also publish notice of such application for eight weeks in a daily or weekly newspaper published in the county or counties in which the project or any part thereof or the lands affected thereby are situated.

(*f*) To prescribe rules and regulations for the establishment of a system of accounts and for the maintenance thereof by licensees hereunder; to examine all books and accounts of such licensees at any time; to require them to submit at such time or times as the commission may require statements and reports, including full information as to assets and liabilities, capitalization, net investment and reduction thereof, gross receipts, interest due and paid, depreciation and other reserves, cost of project, cost of maintenance and operation of the project, cost of renewals and replacements of the project works, and as to depreciation of the project works and as to production, transmission, use and sale of power; also to require any licensee to make adequate provision for currently determining said costs and other facts. All such statements and reports shall be made upon oath, unless otherwise specified,

and in such form and on such blanks as the commission may require. Any person who, for the purpose of deceiving, makes or causes to be made any false entry in the books or the accounts of such licensee, and any person who, for the purpose of deceiving, makes or causes to be made any false statement or report in response to a request or order or direction from the commission for the statements and reports herein referred to, shall, upon conviction, be fined not more than $2000 or imprisoned not more than five years, or both.

(*g*) To hold hearings and to order testimony to be taken by deposition at any designated place in connection with the application for any permit or license, or the regulation of rates, service or securities, or the making of any investigation, as provided in this act; and to require by subpoena, signed by any member of the commission, the attendance and testimony of witnesses and the production of documentary evidence from any place in the United States, and in case of disobedience to a subpoena the commission may invoke the aid of any court of the United States in requiring the attendance and testimony of witnesses and the production of documentary evidence. Any member, expert or examiner of the commission may, when duly designated by the commission for such purposes, administer oaths and affirmations, examine witnesses and receive evidence. Depositions may be taken before any person designated by the commission or by its executive secretary, and empowered to administer oaths, shall be reduced to writing by such person or under his direction and subscribed by the deponent. Witnesses summoned before the commission shall be paid the same fees and mileage that are paid witnesses in the courts of the United States, and witnesses whose depositions are taken and persons taking the same shall severally be entitled to the same fees as are paid for like services in the courts of the United States.

(*h*) To perform any and all acts, to make such rules and regulations and to issue such orders not inconsistent with this act as may be necessary and proper for the purpose of carrying out the provisions of this act.

Preliminary Permits

Sec. 5. That each preliminary permit issued under this act shall be for the sole purpose of maintaining priority of application for a license under the terms of this act for such period or periods, not exceeding a total of three years, as in the discretion of the commission may be necessary for making examinations and surveys, for preparing maps, plans, specifications and estimates, and for making financial arrangements. Each such permit shall set forth the conditions under which priority shall be maintained and a license issued. Such permits shall not be transferable and may be canceled by order of the commission upon failure of permittees to comply with the conditions thereof.

Fifty-Year Licenses

Sec. 6. That licenses under this act shall be issued for a period of not exceeding fifty years. Each such license shall be conditioned upon acceptance by the licensee of all the terms and conditions of this act and such further conditions, if any, as the commission shall prescribe in conformity with this act, which said terms and conditions and the acceptance thereof shall be expressed in said license. Licenses may be revoked only for the reasons and in the manner prescribed under the provisions of this act, and may be altered or surrendered only upon mutual agreement between the licensee and the commission after ninety days' public notice.

Preference to States and Municipalities

Sec. 7. That in issuing preliminary permits hereunder or licenses where no preliminary permit has been issued and in issuing licenses to new licensees under Section 15 hereof the commission shall give preference to applications therefor by states and municipalities, provided the plans for the same are deemed by the commission equally well adapted, or shall within a reasonable time to be fixed by the commission be made equally well adapted, to conserve and utilize in the public interest the navigation and water resources of the region; and as between other applicants, the commission may give preference to the applicant the plans of which it finds and determines are best adapted to develop, conserve and utilize in the public interest the navigation and water resources of the region, if it is satisfied as to the ability of the applicant to carry out such plans.

That whenever, in the judgment of the commission, the development of any project should be undertaken by the United States itself, the commission shall not approve any application for such project by any citizen, association, corporation, state or municipality, but shall cause to be made such examinations, surveys, reports, plans and estimates of the cost of the project as it may deem necessary, and shall submit its findings to Congress with such recommendations as it may deem appropriate concerning the construction of such project or completion of any project upon any government dam by the United States.

The commission is hereby authorized and directed to investigate and, on or before the first day of January, 1921, report to Congress the cost and, in detail, the economic value of the power plant outlined in project numbered three, House Document numbered 1400, Sixty-second Congress, third session, in view of existing conditions, utilizing such study as may heretofore have been made by any department of the government; also in connection with such project to submit plans and estimates of cost necessary to secure an increased and adequate water supply for the District of Columbia. For this purpose the sum of $25,000, or so much thereof as may be necessary, is hereby appropriated.

Transfer of Licenses

Sec. 8. That no voluntary transfer of any license, or of the rights thereunder granted, shall be made without the written approval of the commission; and any successor or assign of the rights of such licensee, whether by voluntary transfer, judicial sale, foreclosure sale or otherwise, shall be subject to all the conditions of the license under which such rights are held by such licensee and also subject to all the provisions and conditions of this act to the same extent as though such successor or assign were the original licensee hereunder: Provided, that a mortgage of trust deed or judicial sales made thereunder or under tax sales shall not be deemed voluntary transfers within the meaning of this section.

Information Required of Applicants

Sec. 9. That each applicant for a license hereunder shall submit to the commission—

(*a*) Such maps, plans, specifications and estimates of cost as may be required for a full understanding of the proposed project. Such maps, plans and specifications when approved by the commission shall be made a part of the license; and thereafter no change shall be made in said maps, plans or specifications until such changes shall have been approved and made a part of such license by the commission.

(*b*) Satisfactory evidence that the applicant has complied with the requirements of the laws of the state or states within which the proposed project is to be located with respect to bed and banks and to the appropriation, diversion and use of water for power purposes and with respect to the right to engage in the business of developing, transmitting, and distributing power, and in any other business necessary to effect the purposes of a license under this act.

(*c*) Such additional information as the commission may require.

Conditions of Licenses

Sec. 10. That all licenses issued under this act shall be on the following conditions:

(*a*) That the project adopted, including the maps, plans and specifications, shall be such as in the judgment of the commission will be best adapted to a comprehensive scheme of improvement and utilization for the purposes of navigation, of water-power development and of other beneficial public uses; and if necessary in order to secure such scheme the commission shall have authority to require the modification of any project and of the plans and specifications of the project works before approval.

(*b*) That except when emergency shall require for the protection of navigation, life, health or property, no substantial alteration or addition not in conformity with the approved plans shall be made to any dam or other project works constructed hereunder of a capacity in excess of one hundred horsepower without prior approval of the commission; and any emergency alteration or addition so made shall thereafter be subject to such modification and changes as the commission may direct.

(*c*) That the licensee shall maintain the project works in a condition of repair adequate for the purposes of navigation and for the efficient operation of said works in the development and transmission of power, shall make all necessary renewals and replacements, shall establish and maintain adequate depreciation reserves for such purposes, shall so maintain and operate said works as not to impair navigation, and shall conform to such rules and regulations as the commission may from time to time prescribe for the protection of life, health and property. Each licensee hereunder shall be liable for all damages occasioned to the property of others by the construction, maintenance or operation of the project works, or of the works appurtenant or accessory thereto, constructed under the license, and in no event shall the United States be liable therefor.

(*d*) That after the first twenty years of operation out of surplus earned thereafter, if any, accumulated in excess of a specified reasonable rate of return upon the actual, legitimate investment of a licensee in any project or projects under license the licensee shall establish and maintain amortization reserves, which reserves shall, in the discretion of the commission, be held until the termination of the license or be applied from time to time in reduction of the net investment. Such specified rate of return and the proportion of such surplus earnings to be paid into and held in such reserves shall be set forth in the license.

(*e*) That the licensee shall pay to the United States reasonable annual charges in an amount to be fixed by the commission for the purpose of reimbursing the United States for the costs of the administration of this act; for recompensing it for the use, occupancy and enjoyment of its lands or other property, and for the expropriation to the government of excessive profits until the respective states shall make provision for preventing excessive profits or for the expropriation thereof to themselves, or until the period of amortization as herein provided is reached, and

in fixing such charges the commission shall seek to avoid increasing the price to the consumers of power by such charges, and charges for the expropriation of excessive profits may be adjusted from time to time by the commission as conditions may require: Provided, that when licenses are issued involving the use of government dams or other structures owned by the United States or tribal lands embraced within Indian reservations the commission shall fix a reasonable annual charge for the use thereof, and such charges may be readjusted at the end of twenty years after the beginning of operations and at periods of not less than ten years thereafter in a manner to be described in each license: Provided, that licenses for the development, transmission or distribution of power by states or municipalities shall be issued and enjoyed without charge to the extent such power is sold to the public without profit or is used by such state or municipality for state or municipal purposes except that as to projects constructed or to be constructed by states or municipalities primarily designed to provide or improve navigation licenses therefor shall be issued without charge; and that licenses for the development, transmission or distribution of power for domestic, mining or other beneficial use in projects of not more than one hundred horsepower capacity may be issued without charge except on tribal lands within Indian reservations; but in no case shall a license be issued free of charge for the development and utilization of power created by any government dam, and that the amount charged therefor in any license shall be such as determined by the commission.

(*f*) That whenever any licensee hereunder is directly benefited by the construction work of another licensee, a permittee, or of the United States of a storage reservoir or other headwater improvement, the commission shall require as a condition of the license that the licensee so benefited shall reimburse the owner of such reservoir or other improvement for such part of the annual charges for interest, maintenance and depreciation thereon as the commission may deem equitable. The proportion of such charges to be paid by any licensee shall be determined by the commission. Whenever such reservoir or other improvement is constructed by the United States the commission shall assess similar charges against any licensee directly benefited thereby, and any amount so assessed shall be paid into the Treasury of the United States, to be reserved and appropriated as a part of the special fund for headwater improvement as provided in Section 17 hereof.

(*g*) Such further conditions not inconsistent with the provisions of this act as the commission may require.

(*h*) That combinations, agreements, arrangements or understandings, express or implied, to limit the output of electrical energy, to restrain trade, or to fix, maintain or increase prices for electrical energy or service are hereby prohibited.

(*i*) In issuing licenses for a minor part only of a complete project, or for a complete project of not more than one hundred horsepower capacity, the commission may in its discretion waive such conditions, provisions and requirements of this act, except the license period of fifty years, as it may deem to be to the public interest to waive under the circumstances: Provided, that the provisions hereof shall not apply to lands within Indian reservations.

Promotion of Needs of Navigation

Sec. 11. That if the dam or other project works are to be constructed across, along or in any of the navigable waters of the United States, the commission may, in so far as it deems the same reasonably necessary to promote the present and future needs of navigation and consistent with a reasonable investment cost to the

licensee, include in the license any one or more of the following provisions or requirements:

(*a*) That such licensee shall, to the extent necessary to preserve and improve navigation facilities, construct, in whole or in part, without expense to the United States, in connection with such dam, a lock or locks, booms, sluices or other structures for navigation purposes, in accordance with plans and specifications approved by the Chief of Engineers and the Secretary of War and made part of such license.

(*b*) That in case such structures for navigation purposes are not made a part of the original construction at the expense of the licensee, then whenever the United States shall desire to complete such navigation facilities the licensee shall convey to the United States, free of cost, such of its land and its rights-of-way and such right of passage through its dams or other structures, and permit such control of pools as may be required to complete such navigation facilities.

(*c*) That such licensee shall furnish free of cost to the United States power for the operation of such navigation facilities, whether constructed by the licensee or by the United States.

Construction of Locks

Sec. 12. That whenever application is filed for a project hereunder involving navigable waters of the United States, and the commission shall find upon investigation that the needs of navigation require the construction of a lock or locks or other navigation structures, and that such structures cannot, consistent with a reasonable investment cost to the applicant, be provided in the manner specified in Section 11, Subsection (*a*) hereof, the commission may grant the application with the provision to be expressed in the license that the licensee will install the necessary navigation structures if the government fails to make provision therefor within a time to be fixed in the license and cause a report upon such project to be prepared, with estimates of cost of the power of development and of the navigation structures, and shall submit such report to Congress with such recommendations as it deems appropriate concerning the participation of the United States in the cost of construction of such navigation structures.

Two-year Limit for Beginning Works

Sec. 13. That the licensee shall commence the construction of the project works within the time fixed in the license, which shall not be more than two years from the date thereof, shall thereafter in good faith and with due diligence prosecute such construction, and shall within the time fixed in the license complete and put into operation such part of the ultimate development as the commission shall deem necessary to supply the reasonable needs of the then available market, and shall from time to time thereafter construct such portion of the balance of such development as the commission may direct, so to supply adequately the reasonable market demands until such development shall have been completed. The periods for the commencement of construction may be extended once but not longer than two additional years, and the period for the completion of construction carried on in good faith and with reasonable diligence may be extended by the commission when not incompatible with the public interests. In case the licensee shall not commence actual construction of the project works, or of any specified part thereof, within the time prescribed in the license or as extended by the commission, then, after due notice given, the license shall, as to such project works or part thereof, be terminated

upon written order of the commission. In case the construction of the project works, or of any specified part thereof, have been begun but not completed within the time prescribed in the license, or as extended by the commission, then the Attorney General, upon the request of the commission, shall institute proceedings in equity in the district court of the United States for the district in which any part of the project is situated for the revocation of said license, the sale of the works constructed and such other equitable relief as the case may demand, as provided for in Section 26 hereof.

Privilege of Recapture by United States

Sec. 14. That upon not less than two years' notice in writing from the commission the United States shall have the right upon, on or after the expiration of any license, to take over and thereafter to maintain and operate any project or projects as defined in Section 3 hereof, and covered in whole or in part by the license, or the right to take over upon mutual agreement with the licensee all property owned and held by the licensee then valuable and serviceable in the development, transmission or distribution of power and which is then dependent for its usefulness upon the continuance of the license, together with any lock or locks or other aids to navigation constructed at the expense of the licensee, upon the condition that before taking possession it shall pay the net investment of the licensee in the project or projects taken, not to exceed the fair value of the property taken, plus such reasonable damages, if any, to property of the licensee valuable, serviceable and dependent as above set forth, but not taken, as may be caused by the severance therefrom of property taken, and shall assume all contracts entered into by the license with the approval of the commission. The net investment of the licensee in the project or projects so taken and the amount of such severance damages, if any, shall be determined by agreement between the commission and the licensee, and in case they can not agree, by proceedings in equity instituted by the United States in the district court of the United States in the district within which any such property may be located: Provided, that such net investment shall not include or be affected by the value of any lands, rights-of-way or other property of the United States licensed by the commission under this act, by the license, or by good will, going value or prospective revenues: Provided further, that the values allowed for water rights, rights-of-way, lands or interest in lands shall not be in excess of the actual reasonable cost thereof at the time of acquisition by the licensee: Provided, that the right of the United States or any state or municipality to take over, maintain and operate any project licensed under this act at any time by condemnation proceedings upon payment of just compensation is hereby expressly reserved.

Provision for New License

Sec. 15. That if the United States does not, at the expiration of the original license, exercise its right to take over, maintain and operate any project or projects of the licensee, as provided in Section 14 hereof, the commission is authorized to issue a new license to the original licensee upon such terms and conditions as may be authorized or required under the then existing laws and regulations, or to issue a new license under said terms and conditions to a new licensee, which license may cover any project or projects covered by the original license, and shall be issued on the condition that the new licensee shall, before taking possession of such project or projects, pay such amount and assume such contracts as the United States is

required to do, in the manner specified in Section 14 hereof: Provided, that in the event the United States does not exercise the right to take over or does not issue a license to a new licensee, or issue a new license to the original licensee, upon reasonable terms, then the commission shall issue from year to year an annual license to the then licensee under the terms and conditions of the original license until the property is taken over or a new license is issued as aforesaid.

War Powers of Government

Sec. 16. That when in the opinion of the President of the United States, evidenced by a written order addressed to the holder of any license hereunder, the safety of the United States demands it, the United States shall have the right to enter upon and take possession of any project or part thereof, constructed, maintained or operated under said license, for the purpose of manufacturing nitrates, explosives or munitions of war, or for any other purpose involving the safety of the United States, to retain possession, management and control thereof for such length of time as may appear to the President to be necessary to accomplish said purposes, and then to restore possession and control to the party or parties entitled thereto; and in the event that the United States shall exercise such right it shall pay to the party or parties entitled thereto just and fair compensation for the use of said property as may be fixed by the commission upon the basis of a reasonable profit in time of peace, and the cost of restoring said property to as good condition as existed at the time of the taking over thereof, less the reasonable value of any improvements that may be made thereto by the United States and which are valuable and serviceable to the licensee.

Indian Reservation Proceeds

Sec. 17. That all proceeds from any Indian reservation shall be placed to the credit of the Indians of such reservation. All other charges arising from licenses hereunder shall be paid into the Treasury of the United States, subject to the following distribution: Twelve and one-half per centum thereof is hereby appropriated to be paid into the Treasury of the United States and credited to "miscellaneous receipts"; 50 per centum of the charges arising from licenses hereunder for the occupancy and use of public lands, national monuments, national forests and national parks shall be paid into, reserved and appropriated as a part of the reclamation fund created by the act of Congress known as the reclamation act, approved June 17, 1902; and 37½ per centum of the charges arising from licenses hereunder for the occupancy and sue of national forests, national parks, public lands and national monuments, from development within the boundaries of any state, shall be paid by the Secretary of the Treasury to such state; and 50 per centum of the charges arising from all other licenses hereunder is hereby reserved and appropriated as a special fund in the Treasury to be expended under the direction of the Secretary of War in the maintenance and operation of dams and other navigation structures owned by the United States or in the construction, maintenance or operation of headwater or other improvements of navigable waters of the United States.

Operation of Navigation Facilities

Sec. 18. That the operation of any navigation facilities which may be constructed as a part of or in connection with any dam or diversion structure built under the provisions of this act, whether at the expense of a licensee hereunder or

of the United States, shall at all times be controlled by such reasonable rules and regulations in the interest of navigation, including the control of the level of the pool caused by such dam or diversion structure, as may be made from time to time by the Secretary of War. Such rules and regulations may include the maintenance and operation by such licensee at its own expense of such lights and signals as may be directed by the Secretary of War and such fishways as may be prescribed by the Secretary of Commerce; and for willful failure to comply with any such rule or regulation such licensee shall be deemed guilty of a misdemeanor, and upon conviction thereof shall be punished as provided in Section 25 hereof.

Regulation of Rates and Charges

Sec. 19. That as a condition of the license every licensee hereunder which is a public service corporation or a person, association or corporation owning or operating any project and developing, transmitting or distributing power for sale or use in public service shall abide by such reasonable regulation of the services to be rendered to customers or consumers of power, and of rates and charges of payment therefor, as may from time to time be prescribed by any duly constituted agency of the state in which the service is rendered or the rate charged. That in case of the development, transmission or distribution or use in public service of power by any licensee hereunder or by its customer engaged in public service within a state which has not authorized and empowered a commission, or other agency or agencies within said state to regulate and control the services to be rendered by such licensee or by its customer engaged in public service, or the rates and charges of payment therefor, or the amount or character of securities to be issued by any of said parties, it is agreed as a condition of such license that jurisdiction is hereby conferred upon the commission, upon complaint of any person aggrieved or upon its own initiative, to exercise such regulation and control until such time as the state shall have provided a commission or other authority for such regulation and control: Provided that the jurisdiction of the commission shall cease and determine as to each specific matter of regulation and control prescribed in this section as soon as the state shall have provided a commission or other authority for the regulation and control of that specific matter.

Interstate and Foreign Commerce

Sec. 20. That when said power or any part thereof shall enter into interstate or foreign commerce the rates charged and the service rendered by any such licensee, or by any subsidiary corporation the stock of which is owned or controlled directly or indirectly by such licensee, or by any person, corporation or association purchasing power from such licensee for sale and distribution or use in public service shall be reasonable, non-discriminatory and just to the customer and all unreasonable, discriminatory and unjust rates of services are hereby prohibited and declared to be unlawful; and whenever any of the states directly concerned has not provided a commission or other authority to enforce the requirements of this section within such state or to regulate and control the amount and character of securities to be issued by any of such parties, or such states are unable to agree through their properly constituted authorities on the services to be rendered or on the rates or charges of payment therefor, or on the amount or character of securities to be issued by any of said parties, jurisdiction is hereby conferred upon the commission, upon complaint of any person aggrieved, upon the request of any state concerned, or upon

its own initiative, to enforce the provisions of this section, to regulate and control so much of the services rendered and of the rates and charges of payment therefor as constitute interstate or foreign commerce and to regulate the issuance of securities by the parties included within this section, and securities issued by the licensee subject to such regulations shall be allowed only for the bona fide purpose of financing and conducting the business of such licensee.

The administration of the provisions of this section, so far as applicable, shall be according to the procedure and practice in fixing and regulating the rates, charges and practices of railroad companies as provided in the act to regulate commerce, approved Feb. 4, 1887, as amended, and that the parties subject to such regulation shall have the same rights of hearing, defense and review as said companies in such cases.

In any valuation of the property of any licensee hereunder for purposes of rate-making no value shall be claimed by the licensee or allowed by the commission for any project or projects under license in excess of the value or values prescribed in Section 14 hereof for the purposes of purchase by the United States, but there shall be included the cost to such licensee of the construction of the lock or locks or other aids of navigation and all other capital expenditures required by the United States, and no value shall be claimed or allowed for the rights granted by the commission or by this act.

Right of Eminent Domain

Sec. 21. That when any licensee cannot acquire by contract or pledges an unimproved dam site or the right to use or damage the lands or property of others necessary to the construction, maintenance or operation of any dam, reservoir, diversion structure or the works appurtenant or accessory thereto, in conjunction with an improvement which in the judgment of the commission is desirable and justified in the public interest for the purpose of improving or developing a waterway or waterways for the use or benefit of interstate or foreign commerce, it may acquire the same by the exercise of the right of eminent domain in the district court of the United States for the district in which such land or other property may be located, or in the state courts. The practice and procedure in any action or proceeding for that purpose in the district court of the United States shall conform as nearly as may be with the practice and procedure in similar action or proceeding in the courts of the state where the property is situated: Provided, that United States district courts shall only have jurisdiction of cases when the amount claimed by the owner of the property to be condemned exceeds $3000.

Extension of Contracts

Sec. 22. That whenever the public interest requires or justifies the execution by the licensee of contracts for the sale and delivery of power for periods extending beyond the date of termination of the license, such contracts may be entered into upon the joint approval of the commission and of the public service commission or other similar authority in the state in which the sale or delivery of power is made, or if sold or delivered in a state which has no such public service commission, then upon the approval of the commission, and thereafter, in the event of failure to issue a new license to the original licensee at the termination of the license, the United States or the new licensee, as the case may be, shall assume and fulfill all such contracts.

Existing Permits and Rights-of-Way Not Affected

Sec. 23. That the provisions of this act shall not be construed as affecting any permit or valid existing rights-of-way heretofore granted, or as confirming or otherwise affecting any claim or as affecting any authority heretofore given pursuant to law, but any person, association, corporation, state or municipality holding or possessing such permit, right-of-way or authority may apply for a license hereunder, and upon such application the commission may issue to any such applicant a license in accordance with the provisions of this act, and in such case the provisions of this act shall apply to such applicant as a licensee hereunder: Provided, that when application is made for a license under this section for a project or projects already constructed, the fair value of said project or projects, determined as provided in this section, shall for the purposes of this act and of said license be deemed to be the amount to be allowed as the net investment of the applicant in such project or projects as of the date of such license, or as of the date of such determination, if license has not been issued. Such fair value may, in the discretion of the commission, be determined by mutual agreement between the commission and the applicant, or, in case they cannot agree, jurisdiction is hereby conferred upon the district court of the United States in the district within which such project or projects may be located, upon the application of either party, to hear and determine the amount of such fair value.

That any person, association, corporation, state or municipality intending to construct a dam or other project works across, along, over or in any stream or part thereof, other than those defined herein as navigable waters and over which Congress has jurisdiction under its authority to regulate commerce between foreign nations and among the several states, may in their discretion file declaration of such intention with the commission, whereupon the commission shall cause immediate investigation of such proposed construction to be made, and if upon investigation it shall find that the interests of interstate or foreign commerce would be affected by such proposed construction, such person, association, corporation, state or municipality shall not proceed with such construction until it shall have applied for and shall have received a license under the provisions of this act. If the commission shall not so find, and is no public lands or reservations are affected, permission is hereby granted to construct such dam or other project works in such stream upon compliance with state laws.

Reservation of Land Applied for Against Entry

Sec. 24. That any lands of the United States included in any proposed project under the provisions of this act shall from the date of filing of application therefor be reserved from entry, location or other disposal under the laws of the United States until otherwise directed by the commission or by Congress. Notice that such application has been made, together with the date of filing thereof and a description of the lands of the United States affected thereby, shall be filed in the local land office for the district in which such lands are located. Whenever the commission shall determine that the value of any lands of the United States so applied for, or heretofore or hereafter reserved or classified as power sites, will not be injured or destroyed for the purposes of power developed by location, entry or selection under the public land laws, the Secretary of the Interior, upon notice of such determination, shall declare such lands open to location, entry or selection, subject to and with a reservation of the right of the United States or its permittees or licensees to enter upon,

occupy and use any part or all of said lands necessary, in the judgment of the commission, for the purposes of this act, which right shall be expressly reserved in every patent issued for such lands; and no claim or right to compensation shall accrue from the occupation or use of any of said lands for said purposes. The United States or any licensee for any such lands hereunder may enter thereupon for the purposes of this act, upon payment of any damages to crops, buildings or other improvements caused thereby to the owner thereof, or upon giving a good and sufficient bond to the United States for the use and benefit of the owner to secure the payment of such damages as may be determined and fixed in an action brought upon the bond in a court of competent jurisdiction, said bond to be in the form prescribed by the commission: Provided, that locations, entries, selections or filings heretofore made for lands reserved as water-power sites or in connection with water-power development or electrical transmission may proceed to approval or patent under and subject to the limitations and conditions in this section contained.

Penalty for Non-compliance

Sec. 25. That any licensee or any person who shall willfully fail or who shall refuse to comply with any of the provisions of this act, or with any of the conditions made a part of any license issued hereunder, or with any subpoena of the commission, or with any regulation or lawful order of the commission, or of the Secretary of War, or of the Secretary of Commerce as to fishways, issued or made in accordance with the provisions of this act, shall be deemed guilty of a misdemeanor, and on conviction thereof shall, in the discretion of the court, be punished by a fine of not exceeding $1000, in addition to other penalties herein prescribed or provided by law; and every month any such licensee or any such person shall remain in default after written notice from the commission, or from the Secretary of War, or from the Secretary of Commerce, shall be deemed a new and separate offense punishable as aforesaid.

Revocation of Permits or Licenses

Sec. 26. That the Attorney General may, on request of the commission or of the Secretary of War, institute proceedings in equity in the district court of the United States in the district in which any project or part thereof is situated for the purpose of revoking for violation of its terms any permit or license issued hereunder, or for the purpose of remedying or correcting by injunction, mandamus or other process any act of commission or omission in violation of the provisions of this act or of any lawful regulation or order promulgated hereunder. The district courts shall have jurisdiction over all of the above-mentioned proceedings and shall have power to issue and execute all necessary process and to make and enforce all writs, orders and decrees to compel compliance with the lawful orders and regulations of the commission and of the Secretary of War, and to compel the performance of any condition imposed under the provisions of this act. In the event a decree revoking a license is entered, the court is empowered to sell the whole or any part of the project or projects under license, to wind up the business of such licensee conducted in connection with such project or projects, to distribute the proceeds to the parties entitled to the same, and to make and enforce such further orders and decrees as equity and justice may require. At such sale or sales the vendee shall take the rights and privileges belonging to the licensee and shall perform the duties of such licensee and assume all outstanding obligations and liabilities of the licensee which

the court may deem equitable in the premises; and at such sale or sales the United States may become a purchaser, but it shall not be required to pay a greater amount than it would be required to pay under the provisions of Section 14 hereof at the termination of the license.

State Laws Not Interfered With

Sec. 27. That nothing herein contained shall be construed as affecting or intending to affect or in any way to interfere with the laws of the respective states relating to the control, appropriation, use or distribution of water used in irrigation or for municipal or other uses, or any vested right acquired therein.

Right to Amend or Repeal Law

Sec. 28. That the right to alter, amend or repeal this act is hereby expressly reserved; but no such alteration, amendment or repeal shall affect any licensee theretofore issued under the provisions of this act or the rights of any licensee thereunder.

San Francisco Rights Maintained

Sec. 29. That all acts or parts of acts inconsistent with this act are hereby repealed: Provided, that nothing herein contained shall be held or construed to modify or repeal any of the provisions of the act of Congress approved Dec. 19, 1913, granting certain rights-of-way to the city and county of San Francisco, in the State of California: Provided further, that Section 18 of an act making appropriations for the construction, repair and preservation of certain public works on rivers and harbors, and for other purposes, approved Aug. 8, 1917, is hereby repealed.

APPENDIX III

STANDARD TESTING CODE FOR HYDRAULIC TURBINES

The following Code has been prepared by a Committee of the Hydraulic Turbine Manufacturers to assist in avoiding misunderstandings in regard to stipulated performances of hydraulic turbines. It is subject to such revision from time to time as will be required by any new developments in turbine testing methods. The reader is also referred to the draft of the American Society for Mechanical Engineers' Code, published in *Mechanical Engineering*, for April, 1922.

Introduction

1. Intended Scope. Hydraulic turbine tests are of two distinct kinds: First, acceptance tests on completed turbines after installation in the power plant; second, experimental tests either on full-sized turbines or models, carried out at manufacturers' laboratories or at a testing flume. Tests of the first kind are for the purpose of determining the fulfillment or nonfulfillment of contracts between the turbine builders and the purchasers. Tests of the second kind are carried out for the purpose of obtaining experimental data on which the design of an installation may be based; for scientific research work; or for the investigation of special problems. This code is intended to apply only to tests of the first kind. When tests of the second kind are used for determining the performance of a full-sized installation, this application should be made only in accordance with principles which will be stated in section 10, below.

2. Principal Factors, Meaning and Intent of Terms Used. In computing the efficiency of an installation a distinction must be made between the efficiency of the plant and the efficiency of the turbine. The efficiency of the plant may include all losses of energy up to any stated point of delivery, such as the delivery of electric power from the transformers, at the switchboard or at the generator terminals, or may be confined to the total efficiency of the hydraulic installation, for which purpose the power is to be computed as that delivered by the turbine to the generator shaft.

For the purpose of computing the plant efficiency the total or gross head acting on the plant is to be used, and is to be taken as the difference in elevation between the equivalent still-water surface before the water has passed through the racks, to the equivalent still-water surface in the tailrace after discharge from the draft tube. When the water in the forebay in advance of the racks flows with sufficient velocity to make its velocity head an appreciable quantity, the actual elevation of the water surface shall be increased by the amount of this velocity head. The same process shall apply to the point of measurement in the tailrace; that is, the velocity head at the point of measurement in the tailrace shall be added to the actual elevation of the surface, the sum being considered the equivalent still-water elevation.

Except where specifically stated herein, this code shall be understood to apply

to tests of the turbine proper, and the terms power, efficiency, effective head, etc., are to be taken as referring to the turbine. In computing the efficiency of the turbine, the losses through the racks, in the intake to the penstocks, and in the penstocks shall not be charged against the turbine; nor shall the head necessary to set up the velocity required to discharge the water from the end of the draft tube be charged against the turbine. The net or effective head acting on the turbine shall be measured from a point near the intake to the turbine casing in turbines equipped with casings, or from a point immediately over the turbine in turbines having an open-flume setting, to a point in the tailrace in the manner set forth below under the heading "Measurement of Head." Since the turbine cannot develop power without discharging water, a correction for the velocity head required to discharge the water into the tailrace shall be added to the tailwater elevation; and a similar correction applied at the intake to encased turbines, as called for under the heading "Measurement of Head." The power developed by the turbine shall be taken as the mechanical power delivered on the turbine shaft and transmitted by the turbine shaft to the generator or other driven machine or system.

In drawing up a general code it is recognized that under particular circumstances sometimes occurring, methods of measuring or computing certain factors entering into the test different from those specified, may appear possible and reasonable; it is, however, the intent of this code that the meaning of the terms efficiency, effective head, etc., shall be the efficiency, effective head, etc., determined as herein specified, and that such terms shall be understood only as thus defined.

General

3. Inspection. Careful inspection should be made before, during, and after the tests to insure the proper operation of the turbine and conditions of measurement.

The turbine runner, guide vanes, and casing should be inspected before and after test to guard against obstructions clogging the vanes. Any change in performance during a test should be investigated.

4. Operating Conditions During Test. Apparatus installed for the purpose of the test shall not affect the performance of the turbine during the test. When any doubt exists regarding this point, a special experiment shall be carried out to detect any effect of removing and replacing the apparatus in question, other conditions being maintained constant.

The unit shall be in normal operating condition throughout the test, and shall have been operated under load for an aggregate time of at least three days prior to the test.

4. (*a*) **Leakage.** Care should be taken that all air inlets into the draft tube are closed, and that leakage of air into the tube or drawing of air into the penstock intake is not taking place, as indicated by excessive amounts of air in the discharge, or presence of vortices in the intake. Precautions against leakage of water from penstock or turbine casing should be taken, particularly through drain valves, relief valves or other connections. The rate of fall of the standing water surface in the turbine casing below the point of intake through the turbine gates should be observed during shutdown as an indication of possible leakage.

(*b*) **Unsteady Conditions.** Tests should not be made under conditions of changing head, load or speed. Variations of load during an individual run shall not exceed 3 per cent above or 3 per cent below the average load, and variations of head shall not exceed 2 per cent above or 2 per cent below the average head, and variations of speed shall not exceed 1 per cent above or 1 per cent below the average

speed. Instrument calibrations and correction curves should be prepared in advance of the test, and measures taken to enable results to be computed as quickly as possible during the course of the test or before the work of testing shall be considered to have been completed.

5. Calibration of Instruments. Important instruments shall be installed in duplicate and all instruments shall be calibrated both before and after the test. Only the readings of those instruments in which the two calibrations agree shall be used in computing the results. Where results are appreciably altered by reason of instrument calibrations made after the test disagreeing with those made before, the test shall be repeated.

6. Conduct of Test. Both parties to the contract shall be represented and shall have equal rights in determining the methods and conduct of the test.

All points of disagreement shall be settled to the satisfaction of both parties, and the results of the test be agreed on as acceptable, before the test shall be considered terminated or the test equipment removed.

The measurement of the various quantities entering into the computation of turbine power and efficiency shall be in accordance with the following regulations:

Measurement of Power Output

7. (*a*) **By Electrical Measurement of Generator Output and Generator Losses.** In turbines direct-connected to electrical generators the power output of the turbine may be measured as provided below.

The intent of the provisions contained herein is that the power output of the turbine shall be taken as the power output of the generator plus all losses supplied by the turbine up to the point of measurement.

The generator may be tested for efficiency either in the shops of the builder or after installation, the losses being determined either by direct measurement of input and output or by the separate-loss method; the electrical measurements being carried out in accordance with the Standardization Rules of the American Institute of Electrical Engineers of September, 1916, but subject to the provisions contained herein.

The generator losses and efficiency as herein defined are for the generator considered as a dynamometer, and are independent of the performance guarantees of the generator which are not within the scope of this code. The generator efficiency shall be determined for the values of load, power factor, temperature or other conditions existing during the turbine test. When the generator is run during the turbine test at speeds different from that used in the generator test, the generator efficiency shall be corrected for the changes in speed.

When practicable, the generator is to be separately excited during both generator and turbine tests, and the excitation loss is not to be included in computing generator efficiency, and is therefore also to be omitted in computing turbine output during the turbine test.

When determined by the separate-loss method, the generator efficiency in the case of polyphase alternators when separately excited is to be taken as

$$= \frac{\text{(Kilowatt Output at Generator Terminals)}}{\left\{\begin{matrix}\text{Kilowatt}\\ \text{Output}\end{matrix}\right\} + \left\{\begin{matrix}I^2R\text{ ar-}\\ \text{mature}\end{matrix}\right\} + \left\{\begin{matrix}\text{Open cir-}\\ \text{cuit core}\\ \text{loss}\end{matrix}\right\} + \left\{\begin{matrix}\text{Stray Load-}\\ \text{Losses}\end{matrix}\right\} + \left\{\begin{matrix}\text{Generator}\\ \text{windage}\\ \text{and friction}\end{matrix}\right\}}$$

all losses being expressed in kilowatts.

The stray load-losses are to be determined, in accordance with Paragraph 458 of the above Standardization Rules of the A.I.E.E., by operating the generator on short-circuit and at the current corresponding to the load to be used in turbine test. This, after deducting the windage and friction and I^2R loss, gives the stray load-loss, the total amount of the loss so determined being included in the above formula, in place of $\frac{1}{2}$ or $\frac{1}{3}$ of this value as sometimes used in former practice. It is, however, understood that whenever under the special conditions of an installation other losses exist, these are to be added, in accordance with the second paragraph of this subdivision, to the stray load losses determined as here given.

The value of generator windage and friction should be directly measured in the shop, or after installation. In units containing direct-connected exciters, the windage and friction may be measured by driving the generator by the exciter run as a motor. When the windage and friction cannot be directly measured, it is to be taken either from shop tests of generators of similar design or from a retardation test made after installation. When possible more than one method should be used in order to obtain a check.

In making such a retardation test, the turbine shaft and runner, or the turbine runner, are to be disconnected when practicable from the generator shaft, in order to enable the windage and friction of the generator alone to be computed. When the turbine shaft or runner cannot be disconnected, the generator windage and friction are to be computed by deducting from the total windage and friction that of the turbine, which for this purpose may be found with sufficient accuracy from the formula:

Turbine windage and friction in kw. $= KBD^4N^3$, in which

B = height of distributor in feet;
D = entrance diameter of runner in feet;
N = revolutions per second;
K = an empirical coefficient which may be taken as 0.000115 as determined from available test data.

In computing the turbine output in the turbine test, this is to be taken as the kilowatt output of generator divided by the generator efficiency as computed above, the result being converted from kilowatts to horse-power.

If an exciter generator is also mounted on the unit shaft and is used to excite the unit under test, then to the output of the main generator computed as above without reference to excitation there is to be added the kilowatt output of exciter divided by the exciter efficiency, this converted to horse-power. It is recommended, however, for simplicity that when possible the exciter shall be run without load and the unit separately excited.

It is recommended to avoid retests and to provide a reliable check, that the electrical instruments used in all tests be installed in duplicate. These instruments, together with the instrument transformers, shall be calibrated both before and after the tests in the same condition as used in the tests. When tests are made under slightly fluctuating loads, the output shall be determined both by indicating wattmeters, read at short intervals, and by recording watt-hour meters. During the turbine test the speed of the unit shall be observed by accurately calibrated tachometer or by revolution counter.

(*b*) **By Absorption Dynamometer.** When a dynamometer, either of the Prony brake, friction disc, or other type, is used, the dynamometer is to be so arranged

as to avoid imposing either end thrust or side thrust on the turbine shaft and bearings, or to avoid adding any friction load which is not measured.

The brake must be capable of operating with the weighing beam floating free of the stops during the entire duration of a run. A dash pot or equivalent device may be used to assist this action if so arranged that the accuracy of measuring the actual torque acting on the turbine shaft is not impaired.

The dynamometer must be so constructed that the lengths of all lever arms used for transmitting and reducing the loads can be accurately measured. The zero load of the dynamometer must be capable of accurate measurement and should not be large in comparison with the net load to be measured.

When power is determined by dynamometer, particular care is to be used in obtaining accurate measurement of the speed of the shaft. If tachometers are used these are to be frequently calibrated by counting the revolutions over an ample length of time. Under usual conditions it is recommended that the speed be directly measured by revolution counter, a tachometer being also used as a check and to indicate variations in speed during a run.

Measurement of Power Input or Water Horse-power

8. Measurement of Head. The intent of the provisions contained herein for the measurement of head is the true determination of the difference between the total energy contained in the water immediately before its entrance into the turbine, and its total energy immediately after its discharge from the draft tube.

The turbine shall be tested if possible under the effective head stated in the contract, and at the speed specified in the contract. If during the test, however, the effective head shall differ from the specified head by an amount not exceeding 10 per cent of the latter, the speed of operation of the turbine shall be adjusted to correspond to the head under which the test is made. The principle is recognized and accepted that if the speed is changed in proportion to the square root of the head, the horse-power output will change in proportion to the three-halves power of the head, and the turbine efficiency will remain the same; that is, when the head differs from the value specified in the contract, the contract guarantees shall be considered to apply if the hydraulic equivalents of the power and speed of the turbines are substituted for the power and speed enumerated in the contract. The hydraulic equivalent of the speed is equal to the specified speed multiplied by the square root of the ratio of the effective head existing during the test to the specified effective head. The hydraulic equivalent of the horse-power is equal to the specified horse-power, multiplied by the three-halves power of the ratio of the effective head existing during the test to the specified effective head.

The test shall not be carried out if the head differs from the contract value by more than 10 per cent either above or below, or if, due to an excess of the head above the contract value, or to a reduction in tailwater elevation, the total draft head approaches within 5 feet of the limiting value corresponding to the barometric height. By total draft head is meant the height of the centerline of the distributor of vertical turbines, or of the highest point of the discharge space of the runner of horizontal turbines above tailwater, added to the velocity head at the point of minimum internal diameter of the runner band.

If during the test it is not practicable to adjust the speed, or if the final calculation should show the speed to have been incorrectly adjusted to suit the head, provided that the discrepancy in speed does not exceed 2 per cent either way from the correct value, the values of power and efficiency shown by the test shall be cor-

rected on the basis of the test curves, of the same or a homologous turbine, made at a testing flume or on a wheel tested in place according to the methods of this code, when such curves are available.

(*a*) **Encased Turbines.** In turbines having closed casings the head is to be measured by at least two, and when possible not less than four piezometers located in a straight portion of the penstock near the turbine casing intake, and by two or more rod or float gauges in the tailrace, placed at points reasonably free from local disturbances.

Such board, rod or float gauges are to be free of velocity effects, and if this is not obtainable when the gauges are set in the open channel, they shall be placed in properly arranged stilling boxes.

All piezometers shall be connected to separate gauges. The conditions of measurement, including velocity distribution, length of straight run of penstock, and conditions of piezometer orifices shall be such that no piezometer shall vary in its readings by more than 20 per cent of the velocity head from the average of all the piezometers in the section of measurement. The piezometer orifices shall be flush with the surface of the penstock wall, the passages shall be normal to the wall, and the wall shall be smooth and parallel with the flow in the vicinity of the orifices. The piezometer orifices shall be approximately $\frac{1}{4}$ inch in diameter. If any piezometer shall be obviously in error due to some local cause or other condition, as indicated by its reading, after the addition of the velocity head, giving a head in excess of the initial available head corresponding to the elevation of the surface of headwater, the source of the discrepancy shall be found and removed, or the piezometer eliminated.

When stilling boxes are used in the tailrace the communication between the box and channel shall consist of one or more piezometer openings in a plane surface parallel to the flow, in order to avoid velocity effects. When board gauges are used at the side of the channel, they shall be flush with the wall surface.

The effective head on the turbine is to be taken as the difference between the elevation corresponding to the pressure in the penstock near the entrance to the turbine casing, and the elevation of the tailwater at the highest point attained by the discharge from the unit under test, the above difference being corrected by adding the velocity head in the penstock at the point of measurement and subtracting the residual velocity head at the end of the draft tube. The velocity head in the penstock shall be taken as the square of the mean velocity at the point of measurement, divided by $2g$; the mean velocity being equal to the quantity of water flowing in cubic feet per second, divided by the cross-sectional area of the penstock at the point of measurement in square feet. The residual velocity head at the end of the draft tube shall be taken as the square of the mean velocity at the end of the draft tube, divided by $2g$, the mean velocity being equal to the quantity flowing in cubic feet per second, divided by the final cross-sectional discharge area of the closed or submerged portion of the draft tube in square feet.

(*b*) **Open Flume Setting.** In the case of turbines set in open flumes, the head is to be measured by board, rod or float gauges located immediately above the center of the turbine, and by board, rod or float gauges in the tailrace, all gauges being placed at points reasonably free from local disturbances, and not less than two gauges being installed in the flume and not less than two in the railrace.

Such gauges are to be free of velocity effects, and if this is not obtainable when the gauges are set in the open channel, they shall be placed in properly arranged stilling boxes. When stilling boxes are used, the communication between the box

and channel shall consist of one or more piezometer openings in a plane surface parallel to the flow, in order to avoid velocity effects. When board gauges are used at the side of the channel, they shall be flush with the wall surface.

The effective head on the turbine is to be taken as the difference between the elevation of the free water surface immediately above the center of the turbine, and the elevation of the tailwater at the highest point attained by the discharge from the unit under test, the above difference being corrected by subtracting the residual velocity head at the end of the draft tube. The residual velocity head at the end of the draft tube shall be taken as the square of the mean velocity at the end of the draft tube, divided by $2g$; the mean velocity being equal to the quantity flowing in cubic feet per second, divided by the final cross-sectional discharge area of the closed or submerged portion of the draft tube, in square feet.

Measurement of Quantity of Water

9. The quantity of water discharged from the turbine is to be measured by one of the following methods. It is recommended that whenever possible more than one of these methods be used, the quantity being taken as the average of the results of two or more simultaneous measurements.

(*a*) **By Weir.** When the quantity of water is measured by weir, weirs with suppressed end contractions shall be used.

The weir or weirs shall if possible be located on the tailrace side of the turbine, and care shall be taken that smooth flow, free from eddies, surface disturbances or the presence of considerable quantities of air in suspension exists in the channel of approach. To insure this condition the weir should not be located too close to the end of the draft tube, and stilling racks and booms should be used when required. The channel of approach should be straight, of uniform cross-section and should be unobstructed by racks and booms, for a length of at least 25 feet from the crest. The racks should be arranged to give approximately uniform velocity across the channel of approach. The uniformity of velocity should be verified by current meter or otherwise.

The head on the weir should be observed by hook gauges placed in stilling boxes communicating through orifices approximately 1 inch in diameter in the sides of the channel of approach, approximately 1 foot below the level of the crest and a distance of not less than 5 or more than 10 times the head upstream therefrom, the head being observed independently at both sides of the channel. In measuring quantities of water corresponding to the loads on which the turbine guarantees are based, the head on the crest shall not be more than two (2) feet or less than one (1) foot, and the velocity of approach shall not be greater than 1 foot per second.

TABLE OF VALUES OF C FOR VARIOUS HEADS AND HEIGHTS OF CREST P

Head h in Feet.	Height of Crest P.										
	4	5	6	7	8	9	10	12	14	16	20
1.0	3.376	3.356	3.344	3.335	3.329	3.325	3.322	3.317	3.314	3.311	3.308
1.2	3.391	3.366	3.350	3.339	3.332	3.326	3.322	3.316	3.311	3.308	3.305
1.4	...	3.379	3.359	3.346	3.336	3.330	3.324	3.316	3.311	3.307	3.303
1.6	...	...	3.370	3.354	3.343	3.334	3.328	3.319	3.312	3.308	3.302
1.8	...	...	...	3.363	3.350	3.340	3.333	3.322	3.315	3.309	3.303
2.0	...	...	...	...	3.358	3.347	3.338	3.325	3.317	3.311	3.304

The discharge shall be computed by the Francis formula in the form given below, using the accompanying table of coefficients. These coefficients are believed to represent the best available information. The values of turbine efficiency resulting from weir tests made in accordance with this code are understood to be efficiencies computed by the use of the formula and coefficients here given.

$$Q = CLh^{3/2},$$

where Q = quantity in cubic feet per second;
L = length of weir in feet;
h = observed head above crest in feet.

P is the height of the crest above the bottom of the channel of approach in feet.

To facilitate computations, all corrections for velocity of approach have been included within the coefficients as given; these are therefore to be used in the formula stated above, the observed head being used without modification.

Note: The above coefficients are the averages of values computed by the following three formulas:

(1) Bazin,

$$Q = \left(0.405 + \frac{0.00984}{h}\right)\left[1 + 0.55\,\frac{h^2}{(p+h)^2}\right]\sqrt{2g}Lh^{3/2};$$

(2) Rehbock,

$$Q = \left[0.605 + \frac{1}{320h - 3} + 0.08\,\frac{h}{p}\right]\frac{2}{3}\sqrt{2g}Lh^{3/2};$$

(3) Fteley-Stearns,

$$Q = 3.31L(h + 1.5h_v)^{3/2} + 0.007L,$$

in which h_v = head due to velocity of approach.

The weir shall be sharp crested, with smooth, vertical crest wall, complete crest contraction, and free overfall. Complete aeration of the nappe shall be secured and observation of the crest conditions and form of nappe shall be made during the test to avoid defective conditions such as adhering nappe, disturbed or turbulent flow, or surging. The sidewalls of the channel shall be smooth and parallel and shall extend downstream beyond the overfall above the level of the crest.

Weirs of a length exceeding approximately twenty times the head (excepting in cases where the velocity of approach is extremely low); or weirs of moderate crest length having high velocities of approach; or those in which the velocity of approach is irregularly distributed, or in which the leading channel is subject to action of the wind, should either be subdivided into a number of sections or the head should be observed not only at both sides but also at intermediate points across the channel of approach. The elevation of the crest should be measured at short intervals of its length in determining the zero readings of the hook gauges.

(*b*) **By Current Meter.** When the discharge is measured by current meter, observations shall be taken by two different types of meter, one type having preferably such characteristics that it will slightly over-register under conditions of turbulent or oblique flow, and the other type having characteristics such that it will under-register under similar conditions. The true velocity obtained by reducing the meter readings on the basis of their still-water ratings may then be taken as a weighted mean between the two series of observations.

As a basis for arriving at the proper weighting of diverging meter results, the

instruments in question should, in addition to their regular still-water ratings, be given simultaneous oscillation or angularity tests at several velocities near those which will probably be experienced during tests. By means of the resulting data, curves showing the over- and under-registering characteristics of each meter may be plotted for varying degrees of obliquity or velocities of oscillation. The total deviation of the two meters may then be noted for any obliquity or lateral velocity. When the relative deviation of the two meters is observed in the field, the curves will then indicate the proportions in which the total deviation should be divided to give the proper correction for each meter.

The point method of observation shall be used and sufficient points shall be obtained to enable both vertical and horizontal velocity curves to be plotted for all portions of the section of measurement. The average velocity shall be determined from these curves by planimeter.

The section of measurement shall be rectangular and smooth flow conditions shall be obtained. It is recommended that in order to avoid abnormally long durations of run a number of meters of each type be used simultaneously. The elevation of water shall be continuously observed during the current meter measurement by stilling boxes, piezometers, or other reliable means. If the supporting rods for the meters are in the same plane as the meters, the area of these rods shall be subtracted from the wetted area of the flume in calculating the quantity. The meter should preferably be supported by rods placed a sufficient distance behind them to avoid any obstructive effect. When a heavy mast or supporting frame is used, it should be designed to offer a minimum disturbance, and should be located several feet downstream from the meters.

(*c*) **By Pitot Tube.** When the Pitot tube method is used, the Pitot tube shall be located in a straight run of penstock or conduit, at a distance equal to at least ten pipe diameters from any upstream bend and at least five diameters from a downstream bend. When the observation is made in a circular pipe or penstock, at least two Pitot tubes shall be arranged to traverse two relatively perpendicular diameters, but in the case of very large penstocks or those having unsymmetrical flow, Pitot tubes shall be arranged to traverse completely or partially the intermediate diameters, giving traverses at forty-five degree intervals.

In determining the velocity in the penstock by the Pitot tubes the static pressure over the cross-section shall be measured by from four to eight carefully constructed piezometers equally spaced around the wall of the penstock at a section 1 foot in advance of the Pitot tube section to avoid the effect of the Pitot tube supporting structure, the penstock being of uniform cross-section between the piezometers and the points of the Pitot tubes. All piezometers shall be connected to separate gauges. The conditions of measurement, including velocity distribution, length of straight run of penstock, and condition of piezometer orifices shall be such that no piezometer shall vary in its readings by more than 10 per cent of the velocity head from the average of all the piezometers. The piezometer orifices shall be flush with the inside surface of the penstock wall, the passages shall be normal to the wall, and the wall shall be smooth and parallel with the flow in the vicinity of the orifices. The orifices shall be $\frac{1}{8}$ inch in diameter.

The velocity at each point in the penstock shall be computed by the formula $V=\sqrt{2gh}$, in which h represents the difference in feet between the total dynamic pressure recorded by the Pitot tube at that point and the average static pressure recorded by the piezometers. The velocities so determined shall be plotted as ordinates against values of the areas of the sections of the penstock corresponding

to the points of measurement as abscissas, a smooth curve being drawn through the points obtained. The mean velocity in the penstock will then be taken as the mean ordinate of the above curve multiplied by 0.976. This coefficient is based on the average of various comparative tests, and is required to correct for oblique or sinuous flow under the usual conditions in straight penstocks.

When the length of straight run of penstock is insufficient or when the flow is disturbed by a severe bend or obstruction upstream from the tube or when the average velocity is less than 5 feet per second, the above coefficient will not apply correctly, the correct value being considerably lower in such cases, which do not, therefore, come within the scope of this code. The coefficient corresponds to a tube, the point of which is $\frac{3}{8}$ inch in diameter with a $\frac{1}{8}$ inch hole, the face being normal to the axis, and at least 3 inches from the nearest surface of the supporting pipe.

(*d*) **By the Screen or Diaphragm Method.** When the screen method is used a sufficient length of straight flume of uniform cross-section shall be constructed with a close-fitting screen filling the cross-section. Provision shall be made for accurately observing the velocity of the screen, preferably by electric contacts and chronograph. The length of run of the screen shall be sufficiently in excess of the portion used for measurement to provide ample space for starting and stopping the screen, so as to insure uniform conditions over the measured portion of the run. In determining the discharge the velocity of the screen shall be multiplied by an area intermediate between the net immersed area of the moving screen and the average area of stream cross-section of the portion of the channel traversed. The variation of the level in the flume shall be observed during the course of the run and the average elevation shall be used in determining the area.

(*e*) **By Titration or Chemical Method.** When the chemical method is used in measuring discharge, care shall be taken to insure that at the point of introducing the dosing solution no portion of the solution shall be carried off by back currents and shall therefore fail to pass to the sampling station, and that the sampling station shall be so placed that no pollution shall be caused by reverse currents, causing fresh water to pass the station from downstream. When necessary, owing to a short length of mixing passage or lack of sufficient disturbance to cause thorough mixing, the dosing pipes shall be so placed that an equal degree of concentration over the entire section of the sampling station shall be obtained. Samples shall be taken from points distributed over the entire sampling section. All necessary precautions shall be observed in taking samples, and in observing the end-point of the reaction during titration.

In short tests, care shall be taken to preserve a uniform rate of introduction of the dosing solution. Preliminary observations shall be made to determine the time required after the dosing is started for uniform conditions to become established at the sampling station; and in the actual tests the dosing shall be continued for double this time before sampling is begun. Uniformity of dilution of samples both with respect to location in the section and the time of taking shall be considered essential for an acceptable test.

Power Tests of Turbine Supplemented by Efficiency Tests of a Model

10. When the conditions of an installation are such as to involve serious difficulty or expense in the application of any of the above methods of water measurement, the tests of the installed turbine may be made when acceptable to both parties without measuring the quantity of water, a homologous model of the turbine

being constructed and tested at the expense of the purchaser, and the power delivered by the installed turbine compared with that computed from the model tests.

This method must not be confused with the practice, which has sometimes been followed, of comparing a turbine with a model having a homologous runner, but dissimilar with respect to setting, draft tube or other parts. The runner, guide vanes, draft tube, casing, or other adjacent water passages should be geometrically similar in the turbine and model; and when so constructed, the power stepped up from the model tests for the hydraulic equivalent of the speed gives a reliable basis of comparison with the power actually obtained from the installed unit.

The power of the model when operating at the hydraulic equivalent of the speed of the large unit in the tests of the latter, at the same proportional gate opening, is to be multiplied by the ratio of the area of the discharge orifices of the large turbine runner to that of the model, and by the three-halves power of the ratio of the head existing in the tests of the large unit to the head in the model tests. When the power so computed agrees exactly with that obtained from the installed unit, the efficiency of the large unit shall be considered to be identical with that of the model; and when the power of the large unit exceeds that thus computed from the model, the efficiency of the large unit shall be considered to be in excess of that of the model. In measuring the gate opening the actual opening of the gates shall be determined, and care shall be taken to avoid errors due to the effect of the pressure on the vanes.

Appendix

11. Special Methods of Water Measurement. The following methods of water measurements may sometimes be applied; these are, however, subject to limitations, and are available only under special conditions. They have not as a rule been in sufficiently general use in turbine testing to permit full reliance to be placed on them until opportunities are afforded for checking them against the methods already given.

(*a*) **By the Bulk or Volumetric Method.** Water measurement by weight or volume is not usually available; the former is limited to laboratory use, which is outside the scope of this code. The bulk method is applicable only when there is available a reservoir of regular form, the volume of which up to various water levels may be accurately measured, and when the following conditions may be observed:

The draw-down or filling of the reservoir must not cause a variation in head on the turbine during a run exceeding the limits specified under section 4 (*b*), namely, a total of 4 per cent of the head. It must be possible to shut off completely all inflow into or outflow from the reservoir. The tightness of the gates and reservoir walls must be tested by closing all gates, and observing over a time of several hours the rate of rise or fall of water level in the reservoir throughout the full range of variation of level which will be used in the turbine test. At the same time any leakage through the turbine head gates is to be measured. The surface elevation in the reservoir is not to be so affected by velocity or wind effects as to cause local variations in level of more than 5 per cent of the total draw-down used in the turbine tests. This variation is to be observed by gauges distributed over the whole reservoir, which are to be read simultaneously at short intervals throughout the test. The effect of surface evaporation shall be investigated and corrections applied to cover it when local conditions are such that it becomes appreciable.

(*b*) **By Venturi Meter.** When it is possible to install a Venturi meter not exceeding in dimensions or differing in conditions from meters whose coefficients have previously been determined in accurate tests, the Venturi meter may be used. The meter shall be similar in proportions to meter previously tested.

(*c*) **By Color Velocity Method.** When the water used by the turbine passes through a conduit suited to the purpose, the color method of quantity determination may be used, depending upon the time of passage between two points of a mass of color injected into the stream. The distance between the two points where the passage of the color is observed must be sufficiently great to render the interval between the times of passage of the color at the two stations large compared to the time required for all the color to pass either station. The conduit must be of sufficiently regular form to permit its cross-sectional areas to be accurately measured at all points between the stations.

(*d*) **By Brine Velocity Method.** A method similar to 11 (*c*) adapted to closed conduits has been used, consisting in the injection of a mass of brine, the time of passage of which is detected by the variation in electrical resistance between two contacts placed in the stream. A pair of such contacts is placed at each station, and the time of passage of the brine between the stations is chronographically recorded by a specially arranged wattmeter. The stations should be arranged as under 11 (*c*).

(*e*) **By Color Density Method.** The coloration or color density may also be employed for approximate tests, this method depending on the use of a colored dosing solution in place of a salt solution in a manner similar to the chemical method of 9 (*e*), observation of the color density replacing the titration.

(*f*) **By Resistance of Salt Solution.** A method which has been used experimentally is similar to the chemical method of 9 (*e*), except that the amount of chemical (salt) in solution is determined by measurement of the electrical resistance of the solution instead of by titration. Care is required to guard against changes in resistance due to small temperature variations.

12. Measurement of Water Horse-power in Plants Containing a Fall Increaser. In case of an installation including a fall increaser or other device utilizing an auxiliary flow for increasing the effective head, the following provisions shall be observed: In determining the efficiency of the turbine proper, considered separately from the fall increaser, the fall increaser shall be closed, and precautions shall be taken that no water except that passing through the turbine shall enter the system between the points at which the head is measured.

In order to determine the performance of the combined hydraulic installation, including both turbine and fall increaser, the total water horse-power shall be computed from the sum of the turbine discharge multiplied by the head on the turbine, and the auxiliary discharge multiplied by the head on the fall increaser. The head on the turbine shall be measured from a point immediately in advance of the point of intake to the turbine proper, as above provided, and the head on the fall increaser shall be measured from a point immediately in advance of the intake gates of the increaser, the head in each case being measured to a point below the junction of the two streams at the outflow from the plant. For the computation of water horse-power it will be necessary to determine the division of the total discharge between the turbine and fall increaser. This may be done when practicable by separately measuring the water admitted to the turbine during the operation of the fall increaser.

If, owing to the arrangement of the fall increaser, it is impracticable to separate the water horse-power of the turbine from that of the fall increaser, the gross efficiency of the combined installation may be determined by measuring the combined total flow, and the total head from a point common to the two flows before entering the plant to a point after they are reunited below the final point of discharge.

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